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BOND BETWEEN CONCRETE AND REINFORCING STEEL

by



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The undersigned certify that they have read, and recommend to the Faculty of Graduate Studies for acceptance, a thesis entitled BOND BETWEEN CONCRETE AND REINFORCING STEEL submitted by Kenneth James Sanderson in partial fulfilment of the requirements for the degree of Master of Science.

ABSTRACT

This thesis deals with a study of the bond between concrete and reinforcement and introduces a new type of pull-out bond test to determine ultimate values for bond resistance between concrete and reinforcing steel, and compares these values to those from conventional pull-out tests.

Three different pull-out tests were conducted. First was the A.S.T.M. Pull-out Test. A reinforcing bar embedded in a 6 inch cube of concrete was pulled out by bearing against the concrete surface from which the bar protruded. The second test was conducted on a 6 inch diameter by 12 inch long concrete cylinder with spiral wire reinforcement around a bar embedded in the concrete. The third test was conducted on a bar embedded in a large block of plain concrete and was tested by bearing against the corners of the block, so as to remove any effects of bearing on the concrete adjacent to the bar.

The variables studied were embedment length, concrete strength, and bar size.

Specimens were fabricated using four different concrete strengths, approximately 3, 4, 5, and 6 k.s.i. for each embedment length. Bar sizes were #3 and #6, with embedment lengths from 1 inch to 8 inches.

Results of the A.S.T.M. Tests verified the fact that the ultimate bond resistance varies as $\sqrt{f_c'}$. Results of the other two tests also

indicated reasonably well that the ultimate bond resistance varied as $\sqrt{f_c'}$.

Comparison of ultimate bond resistance to the L/d ratio for the Spiral Reinforced Cylinder Tests showed that bond decreased with an increase in L/d, but for the same L/d ratio, #6 bars exhibited higher ultimate bond resistance than #3 bars. This could have been a result of the development of a very high bond stress near the unloaded end of the longer embedded bar near failure.

Two different types of failure were exhibited by the Block Pull-out Tests. For smaller L/d ratios, the ultimate bond resistance was very low because failure resulted from the development of a cone of concrete around the bar. This failure was dependent mainly on the tensile strength of the concrete. For the larger L/d ratios a cone also formed, but enough bar remained embedded to result in a bond resistance comparable to that of the Spiral Reinforced Cylinder Test. This further substantiates the hypothesis that the longer bars develop a very high bond stress near the unloaded end of the bar.

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CHAPTER I

INTRODUCTION

1. General Comments

The study of bond between concrete and reinforcing steel has been a concern of engineers for many years. In the early years of reinforced concrete, smooth reinforcing bars were used and they were anchored by hooks or bends at the ends to increase the ultimate bond resistance. Early researchers devised different types of deformations on the surface of steel bars in order to increase the bond resistance. The majority of research conducted until about 1940 was concerned with the bond resistance of different types of deformed bars. Eventually, this led to the development of a standard type of deformed bar which is used today.

Most tests were conducted on pull-out specimens in which the reinforcing bar was embedded in a block or cylinder of concrete and the bar pulled out by bearing against the face of the concrete from which the bar protruded. Some tests were made using beams designed to fail in bond. Since the development of a standard deformed bar, research into bond failures has mainly been carried out using beam specimens as this more closely represents the situation where most bond failures occur in practice.

Pull-out tests have not been used extensively because there does not seem to be a good correlation between the results of pull-out and beam tests. They serve mainly as a means by which the effects of variables such as type of concrete, different types of reinforcing bars and sizes of bars can be studied. The results may not be similar because of the different stress conditions in the two tests. In the pull-out test, the concrete is in compression and the reinforcing bar in tension, while in the beam test, both the concrete and steel are in tension and there is also accompanying beam shear. As the pull-out test is easier to perform, it would be desirable to conduct such a test to give results which would correlate with beam tests.

2. Object

The object of this thesis is to study bond between concrete and reinforcement. A pull-out test was devised which was used together with the standard A.S.T.M. Pull-out Test for comparisons. This test was designed to eliminate effects of bearing on the concrete adjacent to the reinforcing bar as is the case in a conventional pull-out test.

The main problem was to devise a method which would eliminate bearing on the concrete adjacent to the reinforcing bar. This was accomplished, as is described completely in Chapter VI, by casting a bar in a large block of concrete and testing by bearing against this block a sufficient distance away from the bar so the effects of compression in the concrete would not affect the region near the reinforcing bar itself. The concrete in the vicinity of the bar was

loaded by shearing forces which resulted in diagonal tension forces. It was hoped this action would give results similar to beam tests. However, the test would not simulate beam conditions well, as it would not allow cracking similar to that in beams because of greater "cover" on the bar in the pull-out test. Transverse cracking would probably occur, but it would be restrained to a certain extent by the surrounding concrete.

3. Scope

The research carried out was limited primarily to a study of the actual ultimate values of bond resistance not the values determined from measurements of load corresponding to a certain slip of the loaded end of the bar. Load-slip measurements were made, but as discussed later, these were not of great value.

Tests were conducted on three different types of pull-out specimens. These tests were:

(a) A standard pull-out test conducted according to A.S.T.M. Specification C 234-62, in which a bar is cast vertically in a 6 inch cube of concrete and tested similar to a conventional pull-out.

(b) A modified pull-out test conducted on a reinforcing bar embedded in a 6 inch by 12 inch concrete cylinder with a drawn wire spiral placed in the concrete around the bar, and tested similar to a conventional pull-out. This test is referred to as the Spiral Reinforced Cylinder Pull-out Test.

(c) A pull-out test conducted on a reinforcing bar embedded in

a large block of plain concrete, and tested by using the corners of the block as bearing points for pulling the bar. This test is referred to as the Block Pull-out Test.

Tests (b) and (c) were for comparison and test (a) was essentially to verify the hypothesis of ultimate bond resistance being a function of $\sqrt{f_c'}$, and also for comparison with tests (b) and (c).

Beam tests were not conducted in this investigation due to lack of time.

There are many variables which affect the ultimate bond resistance in both pull-out and beam tests. In this investigation, the variables studied were: concrete strength, embedment length, and bar size. The tests described in this thesis are the first in a series of tests to be conducted to study ultimate bond resistance. Effects of additional variables will be studied in future tests.

CHAPTER II

REVIEW OF PREVIOUS INVESTIGATIONS

There has been much research conducted on the subject of ultimate bond resistance. Early investigators using deformed bars were concerned mainly with developing sufficient flexural bond resistance. Upon the recent introduction of deformed high strength reinforcing steel with higher permissible steel stresses, there is also more concern about anchorage length which is also dependent on the ultimate bond resistance. The following review of previous investigations presented here is limited to pull-out type studies, rather than to beam studies.

One of the first papers published on the subject of bond between concrete and reinforcing steel was that by Abrams (1913)*. He tested both pull-out and beam specimens and investigated the effects of many variables. The main variable was the type of reinforcing bar, but other variables included concrete strength, length of embedment, different cylinder diameters for pull-out tests, amount of area of the face of the pull-out specimen which was used for a bearing area during testing, and direction of pulling of bars. He found that by increasing the embedment length to bar diameter ratio, or L/d ratio, the ultimate bond resistance decreased, and for the same L/d ratio, a

* The references cited are listed in the LIST OF REFERENCES on page 84.

smaller diameter bar developed greater ultimate bond resistance than a larger diameter bar. Abrams (1913) conducted pull-out tests with concrete strength varying from about 0 p.s.i. to about 5,000 p.s.i., and concluded that bond resistance increased in proportion to f_c' . This conclusion is contrary to the present hypothesis which state that bond resistance varies as $\sqrt{f_c'}$. A close examination of Abram's (1913) tests indicates that the present hypothesis is satisfactory. In one series of tests, he varied the bearing area by using a washer type bearing plate with different diameters and found there was little change in the ultimate bond resistance for different bearing areas. These results cannot be very conclusive as the concrete relatively close to the reinforcing bar was still in compression.

Papers published in the 1930's were primarily concerned with increasing the ultimate bond resistance by using different types of deformed bars. Wernisch (1937) tested a variety of bars including smooth, threaded, twisted and various types of deformed bars in pull-out and beam tests. His results showed that deformations similar to today's A.S.T.M. Standard gave the best ultimate bond resistance. Davis, Brown, and Kelly (1938) conducted tests using plain bars and found that the ultimate bond resistance had no relationship to f_c' , however, their test results indicate that ultimate bond resistance, expressed as a percentage of f_c' , decreases as f_c' increases. This shows that ultimate bond resistance varies closer to a square root relationship than to a linear relationship. Menzel (1939) presented a paper which studied the effects of several variables on ultimate bond

resistance. One important variable was the orientation of the reinforcing bar during casting of the specimen. Using pull-out tests with different bar orientations he found that the ultimate bond resistance was greatest for bars which were vertical during casting and were pulled opposite to the direction of settlement of the concrete. The next highest ultimate bond resistance was for bars cast horizontally, and the least was for bars cast vertically and pulled in the direction of concrete settlement.

Some researchers investigated the bond stress distribution along the length of a bar in a pull-out or beam test. Watstein (1947) measured strain at various points along a reinforcing bar embedded in a 6 inch diameter concrete cylinder using strain gauges placed on the outside of the bar. He found that for deformed bars, the bond stress increased from zero at the loaded end of the bar, to a maximum a short distance from the loaded end, then decreased toward the free end of the bar. The maximum local stress was in the order of two times the calculated average bond stress for the embedded length of bar. Mains (1951) conducted similar tests, but placed the strain gauges inside a bar which had been cut in half, grooved out slightly, then tack welded back together. His results were similar to Watstein's (1947).

Since the advent of high strength steel reinforcing bars, additional studies of ultimate bond resistance were necessary because the use of this type of steel resulted in higher flexural stresses which in turn resulted in higher bond stresses in certain regions of beams. One of the first investigations performed using high strength

bars was by Mathey and Watstein (1961). They conducted tests on beams and prismatic pull-outs with wire mesh reinforcement around the bars. Reinforcing bars with a yield point of approximately 100,000 p.s.i. were used. The bond failure was designated by excessive slip at either the loaded or free end of the bar. The reason for using excessive slip as a failure criterion is that if the bar would slip a great deal in a beam, large cracks would form and the structure would become unserviceable. In their investigation, a study was made of the relationship between bond stress and steel stress in the beams tested. It was found that at lower loads, the observed bond stress was higher than that calculated by a linear relationship between bond and steel stresses. However, at loads near the ultimate value, the observed values of bond stress approached the computed values, indicating that measurements of steel stress could be used to calculate bond stress near the ultimate value. Mathey and Watstein (1961) adjusted the values of ultimate bond resistance to a common concrete strength on the basis that the ultimate bond resistance was directly proportional to f_c' . In terms of current procedures, this should have been adjusted using $\sqrt{f_c'}$. As with previous researchers, Mathey and Watstein (1961) did not obtain a good correlation between beam and pull-out tests. For #4 bars there was a better comparison because of the absence of cracks in the beam tests.

Probably the easiest method of overcoming the problem of bond is to place a hook on the end of the bar, or to extend the bar a sufficient distance past the point where it is no longer required as tension reinforcement. This length should be sufficient to develop the

tensile capacity of the bar. Two papers published by Ferguson and Thompson (1962 and 1965) deal with this aspect of bond. They were mainly concerned with the embedment length required to develop the full tensile strength of the reinforcing bar in beams. The 1962 paper had results of tests on #3, #7 and #11 bars while the 1965 paper was concerned with #11 and #18S bars. Of the many variables investigated, only concrete strength and embedment length are discussed here, since these variables are pertinent to this thesis. The ultimate bond resistance was based on a slip of 0.01 inches at the loaded end of the bar, which was considered to be about one half the allowable crack width for most structures. Ferguson and Thompson (1962 and 1965) found that if bond resistance was plotted against the embedment length, rather than L/d , a single continuous curve was obtained for all bar sizes, rather than a series of curves for different bar sizes. Tests on #7, #14S and #18S bars of high strength steel were made by Ferguson, Breen, and Thompson (1965). These tests were conducted as pull-outs on prismatic specimens with the bars cast horizontally near one face of the prism. The authors found there was little difference in the bond resistance between specimens which were reinforced with wire spirals and those which had no reinforcement. This applied to long embedment lengths; they believed this may not have been true for shorter embedment lengths. Ferguson, Breen and Thompson (1965) also found that for the larger bars, although they developed a higher ultimate bond resistance, the large slip that occurred reduced the ultimate bond resistance, according to their definition. They also concluded that results from pull-out tests were not a good indication of the

behavior in beams.

Untrauer and Henry (1965) investigated the effects of normal pressure on the concrete in A.S.T.M. Pull-out Tests. Tests were conducted on #6 and #9 bars of high strength steel. Normal pressure was applied to two parallel faces of the specimen using a special loading frame. They conducted some tests with no normal pressure which were used for comparison. They found that the bond resistance varied as $\sqrt{f_c'}$ and that when normal pressure was applied, higher resistances were recorded for the #9 bar.

Perry and Thompson (1966) conducted bond stress distribution tests similar to Mains (1951). They found the maximum bond stress occurred near the unloaded end of the bar for weaker concrete, and near the loaded end for higher strength concrete.

The problem of bond is still under investigation, but the trend now is towards beam tests rather than pull-out tests.

CHAPTER III

PRESENT STUDY

1. General Remarks

Of the investigations reported in the previous chapter, none dealt with a pull-out test in which both the reinforcing bar and concrete adjacent to the bar are in tension. The only report of a slight variation was by Abrams (1913). The area in compression was only a short distance from the reinforcing bar and the results were not significantly different from those with compression over the entire face of the concrete.

The major difference in behavior between beam and pull-out tests seems to be the effect of cracking in beams which increases slip of the bar. In previous pull-out tests, no cracking occurred because the concrete in the specimen was in compression. If a pull-out test could be devised which would place both the bar and concrete in tension and allow the development of transverse cracks, some correlation between such a test and beam tests might be expected.

In this investigation a pull-out test which eliminated bearing on the concrete adjacent to the reinforcing bar was used but the test provided more "cover" on the bar than in a beam specimen, which hindered the development of transverse cracks in the concrete.

2. Variables

The variables considered to be the most important for the initial stage of testing were concrete strength, length of bar embedment and bar size. Concrete strength was varied to study if the bond resistance varied as $\sqrt{f_c'}$. The length of embedment and size of reinforcing bar were varied to see if there was any relationship between bond resistance and the L/d ratio.

Other variables, including type and slump of concrete, orientation of the reinforcing bar during casting, and type of deformations on the bar were kept constant in this initial study. These variables were considered less important and their effects have been studied by previous investigators. The type of concrete was fixed by the materials available locally. Slump of the concrete was maintained at about 3 inches which gave good workability and should produce good bond resistance. All specimens were cast with the reinforcement in a vertical position. All reinforcement conformed to A.S.T.M. Specification 305-56T.

CHAPTER IV

THEORY

Bond is defined by ACI Committee 116 (1962) as "Adhesion of concrete or mortar to reinforcement or to other surfaces against which it is placed." Bond strength is defined as "Resistance to separation of mortar and concrete from reinforcing steel and other materials with which it is in contact."

A bond failure may be divided into the following stages:

(i) At low loads, the resistance is supplied entirely by adhesion between concrete and the reinforcing bar.

(ii) As the load is increased, the bond stress near the loaded end of the bar increases sufficiently to break the adhesion. When the adhesion is broken, the bar will move relative to the concrete, or "slip". As the load is increased further, this action progresses toward the unloaded end of the bar.

(iii) After the adhesion is broken, the concrete between the deformations on the bar will come to bear against the deformations, resulting in an increase in bond resistance. When the load is further increased, the concrete against the deformations will crush due to excessive bearing pressure. In some cases, the concrete may shear on a surface between the tips of the deformations.

(iv) If the concrete crushes, resistance will be provided until the entire amount of concrete between the deformations is crushed, or if shearing occurs, resistance is provided by friction between the surfaces of the concrete. This action progresses towards the unloaded end of the bar until there is excessive slip with little or no increase in the load and the bar finally pulls out of the concrete.

(v) If cracks develop transversely to the bar, as do shear or flexure cracks in a beam, the bond stress at a crack will be zero, and the embedment length is essentially reduced. This results in an increase in bond stress in the remainder of the bar and failure can occur at a lower load than if no cracks developed.

The bond resistance is expressed as a stress. For an embedded bar subjected to a tensile load, the average bond stress is calculated by:

$$u = \frac{P}{\Sigma_O L} \quad (1)$$

where u = bond stress, in p.s.i.

P = load on the bar, in pounds.

Σ_O = nominal perimeter of the bar or bars, in inches.

L = length of embedded reinforcing bar, in inches.

Equation 1 gives the average bond stress for the embedded bar. This assumes the bond stress is constant along the bar which is a simplification of the actual case. For the ultimate bond resistance, the load P is the failure load on the bar.

Slip of the reinforcing bar is a measure of the movement of the reinforcing bar relative to the face of the concrete adjacent to the bar. It is obtained from measurements of the relative movement using dial gauges supported close to the face of the concrete from which the bar protrudes. The elastic deformation in the bar between the concrete and the point of measurement is subtracted from the dial gauge reading to give the slip.

The elastic deformation is given by Equation 2.

$$\delta = \frac{PL}{AE} \quad (2)$$

where δ = elastic deformation, in inches.

P = load on the bar, in pounds.

L = length of bar between the concrete and the point of measurement, in inches.

A = nominal cross-sectional area of the bar, in square inches.

E = Modulus of Elasticity of the bar, in p.s.i.

Slip of the reinforcing bar may be used as a criteria for determining an ultimate value of bond resistance. If the slip is excessive in beams, large cracks may develop, or excessive deflections may result, making the beams unserviceable. If the slip is related to the width of crack that would develop in a beam, the ultimate bond resistance can be determined by the slip criterion. Ferguson, Breen and Thompson (1965) state that the loaded end slip of a pull-out test can be related to one half the crack width for a beam. They define a normal crack width to be of the order of 0.02 inches.

Ultimate bond resistance determined from excessive slip is usually less than that for complete pull-out failure because of the higher stress near the loaded end causing a local failure which results in a large slip near this end.

With deformed reinforcing bars, a transverse force is also produced. Because of the inclination of the deformations, the concrete bearing against the deformations has a component of force transverse to the bar, as well as along the axis of the bar. At high loads, the transverse force may split the concrete if the cover is not great or if there is no auxiliary reinforcement to resist these forces. Splitting of the concrete usually results in a lower ultimate bond resistance than if splitting was prevented.

CHAPTER V

MATERIALS

1. Concrete

Type III, High Early Strength Portland Cement was used in the concrete to reduce the curing time required. The cement was obtained in bags from a local supplier and stored in the laboratory until required.

The aggregate used was obtained from a local supplier and stored in overhead bins in the laboratory until required. The coarse aggregate was crushed rock with 3/4 inch maximum size particles. Results of a typical sieve analysis are shown in TABLE I. The moisture

TABLE I

SIEVE ANALYSIS OF COARSE AGGREGATE

Sieve Size	% Retained	Cummulative % Retained
3/4"	1.1	1.1
3/8"	58.4	59.5
#4	37.5	97.0
Pan	3.0	100.0

content was determined from random samples and found to be 1.66% by weight of aggregate.

The fine aggregate was natural pit-run sand. Results of a typical sieve analysis are shown in TABLE II, indicating a Fineness Modulus of 2.53. The sand was placed in the overhead bin in a saturated condition some time before casting commenced, however, some drying occurred prior to casting which resulted in varying moisture contents throughout the bin. A moisture test on random samples indicated an

TABLE II

SIEVE ANALYSIS OF FINE AGGREGATE

Sieve Size	% Retained	Cummulative % Retained
#4	3.0	3.0
#8	14.7	17.7
#16	9.5	27.2
#30	10.3	37.5
#50	35.8	73.3
#100	21.1	94.4
#200	3.1	--
Pan	2.5	--
	-----	-----
Total	100.0	253.1

average moisture content of 4.54% by weight of sand.

The concrete mix was designed according to the Portland Cement Association Design Method (1963). Concrete strengths of approximately 3, 4, 5, and 6 k.s.i. were chosen so as to give a good variation in strengths. Trial mixes were made and the design altered to give strengths in the required range. As fabrication of the specimens progressed, slight adjustments in the mix were made to attain strengths closer to those desired. The proportions of each mix are shown in TABLE III. The concrete was mixed in a rotary type upright mixer of 9 cubic foot capacity. One batch of about 6 cubic feet was required for the smaller block specimen, and two batches were required for the larger block specimen. Mixing time for each batch of concrete was from five to ten minutes, thus ensuring a uniform mix of the proper consistency. Water from the city supply line was added to the mix until approximately a 3 inch slump was attained. Because the moisture in the sand varied from mix to mix, the slump was maintained constant rather than the amount of water added.

2. Reinforcement

The reinforcing bars used for all the tests were standard deformed bars complying with A.S.T.M. Specification A305-56T. Two sizes, #3 and #6, were used, with the same type of deformations.

Tension tests were conducted on the reinforcement to determine the yield strength and ultimate strength. The yield strength was approximately 55,000 p.s.i. and the ultimate strength approximately 85,000 p.s.i., for both sizes of bars. The bars exhibited a well

TABLE III
CONCRETE DATA

Concrete Compressive Strength	Cement:Sand:Coarse by weight*	Water/Cement ratio*	Slump (in.)	Compressive Strength (p.s.i.)	Splitting Tensile Strength T (p.s.i.)	Modulus of Rupture R (p.s.i.)
3340	1 : 3.26 : 4.11	0.926	3 1/2	3630 3320	274 305	500 460
3900	1 : 2.80 : 3.72	0.848	3	3900 3900	358 323	480 500
4875	1 : 2.48 : 3.43	0.745	3	4900 4850	443 394	599 620
5280	1 : 2.06 : 2.98	0.703	3	5290 5270	438 443	625 610
3145	1 : 3.55 : 4.35	1.000	3	3130 3160	296 305	471 473
3960	1 : 2.80 : 3.72	0.848	3	3990 3930	363 375	556 569
4395	1 : 2.48 : 3.48	0.816	3 1/2	4390 4400	407 394	540 542
5885	1 : 1.53 : 2.49	0.565	3 1/4	5965 5805	425 451	690 614
2780	1 : 3.55 : 4.35	1.066	3	2760 2800	296 288	492 494
3695	1 : 2.80 : 3.72	0.867	3 1/2	3640 3750	372 327	530 522
5080	1 : 2.48 : 3.43	0.773	3	5060 5100	433 394	588 590
6220	1 : 1.53 : 2.49	0.571	3 1/4	6270 6170	455 491	646 636
2645	1 : 3.56 : 4.36	1.042	3 1/4	2690 2600	275 319	522 474
4415	1 : 2.47 : 3.43	0.777	3 1/2	4600 4230	331 393	588 560
4570	1 : 2.81 : 3.73	0.818	3	4700 4440	331 345	599 577
5680	1 : 1.53 : 2.48	0.536	3 1/4	5880 5480	558 522	577 616

* Note - Moisture in the aggregates has been accounted for in these quantities.

Note - Compressive strength is given first and is used as a key for identification with each test, rather than the specimen number because one concrete strength is used for more than one test. The concrete strengths are listed in the order that the specimens were fabricated and tested.

defined yield point and yield plateau similar to mild steel. The specific yield point for each bar is shown in the appropriate table of results.

Bars of this strength were used because they were stocked at the Structural Engineering Laboratory. Higher strength bars would have to be ordered specially and time did not allow this.

Before casting of the specimens, each bar was cleaned with a wire brush to remove any loose rust and mill scale. The end of the bar which was to be embedded in the concrete was ground smooth to obtain an exact embedment length.

The spiral reinforcement for the cylinder tests was fabricated from #2 smooth bars. The spiral had an outside diameter of 4 inches and a pitch of 1 inch. Forming of the spiral was accomplished by bending the bar around a rotating steel cylinder fixed in the jaws of a machinist's lathe. The ends of the bar were wired to the closest turn of the spiral to make a cylindrical shape.

CHAPTER VI

FABRICATION AND TESTING

1. General Remarks

All tests were conducted from May to August, 1966, using the facilities of the Civil Engineering Department. The specimens were fabricated and cured in the Structural Engineering Laboratory. The Block Pull-out specimens were tested in the Structural Engineering Laboratory, and the remainder of the specimens were tested in the Civil Engineering Strength of Materials Laboratory.

The fabrication and testing schedule for a typical set of specimens was as follows:

(a) Fabrication of two series of test specimens.

Each series consisted of an A.S.T.M. Pull-out Test, a Spiral Reinforced Cylinder Pull-out Test and a Block Pull-out Test with the same bar size, embedment length and concrete mix. Tests to determine the Compressive Strength, Splitting Tensile Strength and Modulus of Rupture were made for each series. The Compressive Strength was determined according to A.S.T.M. Specification C39-66; the Splitting Tensile Strength according to A.S.T.M. Specification C496-66; and the Modulus of Rupture according to A.S.T.M. Specification C78-64, using beams 3 1/2 inches by

4 1/2 inches by 16 inches long.

(b) Removal of forms after 24 hours of curing with wet burlap.

(c) Curing under wet burlap for 6 days.

(d) Testing of specimens on the seventh day after fabrication.

2. A.S.T.M. Pull-out Tests

A. Fabrication

Fabrication was carried out according to A.S.T.M. Specification C234-62 for a vertically embedded bar. This consisted of casting a #6 bar in a 6 inch cube of concrete, with the reinforcing bar embedded 6 inches each time. Only one mold was constructed according to specifications, the other was made of plywood since lack of time prevented making a second metal mold. The molds were placed on a small platform with a framework of Dexion slotted steel angles constructed to hold the bar in position during casting of the concrete. FIGURE 1 shows the framework supporting the specimens, in which the concrete was already placed. The A.S.T.M. specimens are first and third from the right. Concrete strength specimens are shown in front of the framework.

Before casting the concrete, the bar was centered in the mold with one end of the bar resting on the bottom. The bar was clamped to the framework to ensure stability during casting. Concrete was placed in the mold in two layers, each layer being tamped 25 times with a standard tamping rod. After the final layer was compacted, the top surface was struck off with a steel trowel making sure the surface of the concrete was level with the top of the mold. Wet burlap, then



FIGURE 1

A.S.T.M. AND SPIRAL REINFORCED CYLINDER TEST SPECIMENS

polyethylene sheet was placed over the specimens. They were cured for 24 hours, after which time the forms were removed. The specimens of each series were placed together and wet burlap placed over the entire group. This curing lasted for 6 days, during which time the burlap was moistened periodically to provide sufficient water for hydration. On the seventh day after fabrication, the burlap was removed and the specimens were allowed to dry for about 1 to 2 hours before testing.

During the curing period, the conditions in the laboratory varied considerably. Temperature varied from 75° F. to 85° F., and relative humidity varied from 25% to 50%.

B. Testing

Testing was conducted in a 200,000 lb capacity Baldwin Testing Machine shown in FIGURE 2. Before testing, a 1 inch thick steel plate was bonded to the loading face of the specimen with Plaster-of-Paris to ensure even distribution of load to the concrete. The specimen was placed on the upper cross-member of the testing machine with the bar protruding down through the cross-member. The bar was then clamped in the chucks of the lower cross-member. A spherical bearing block should have been used to produce a truly axial load in the bar, but a suitable one was not available. However, the reinforcing bar was lined up as carefully as possible to produce an axial load.

Slip of the reinforcing bar was measured using the apparatus shown in FIGURE 3. FIGURE 4 shows the collar used for measuring slip

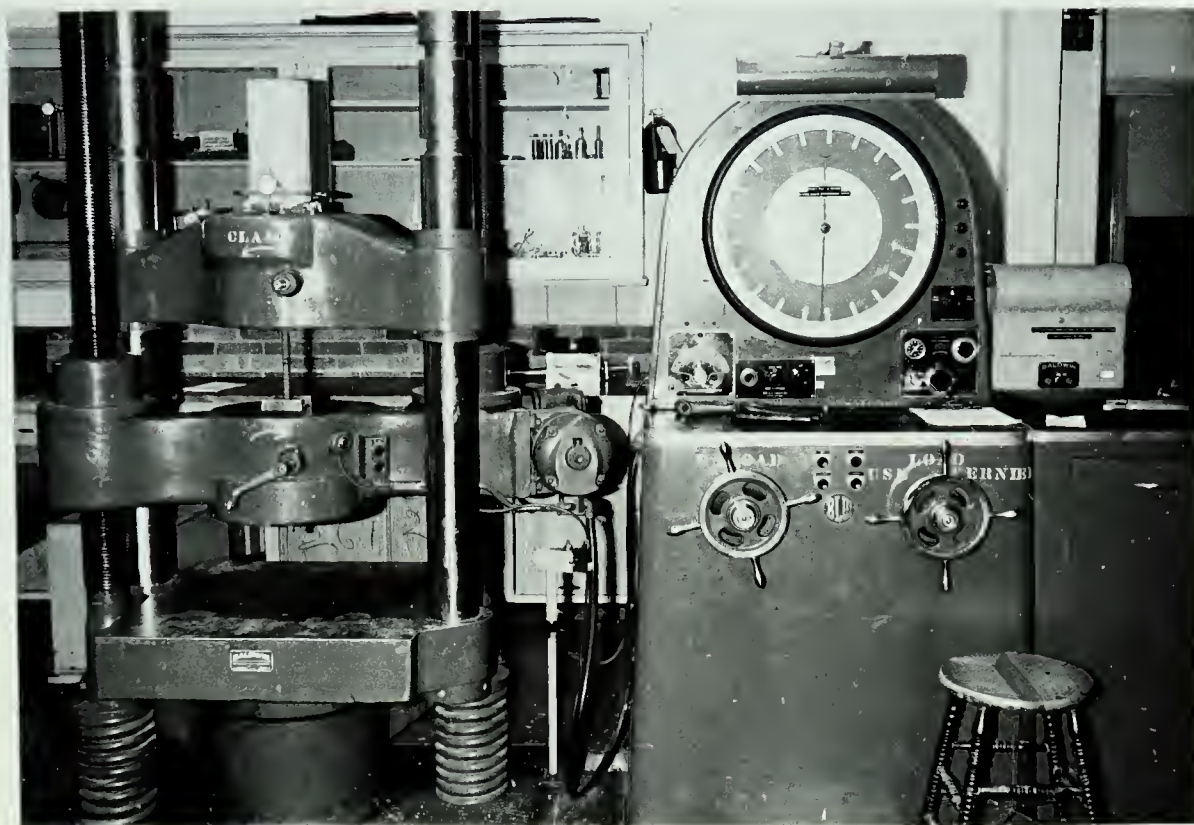


FIGURE 2

BALDWIN TESTING MACHINE

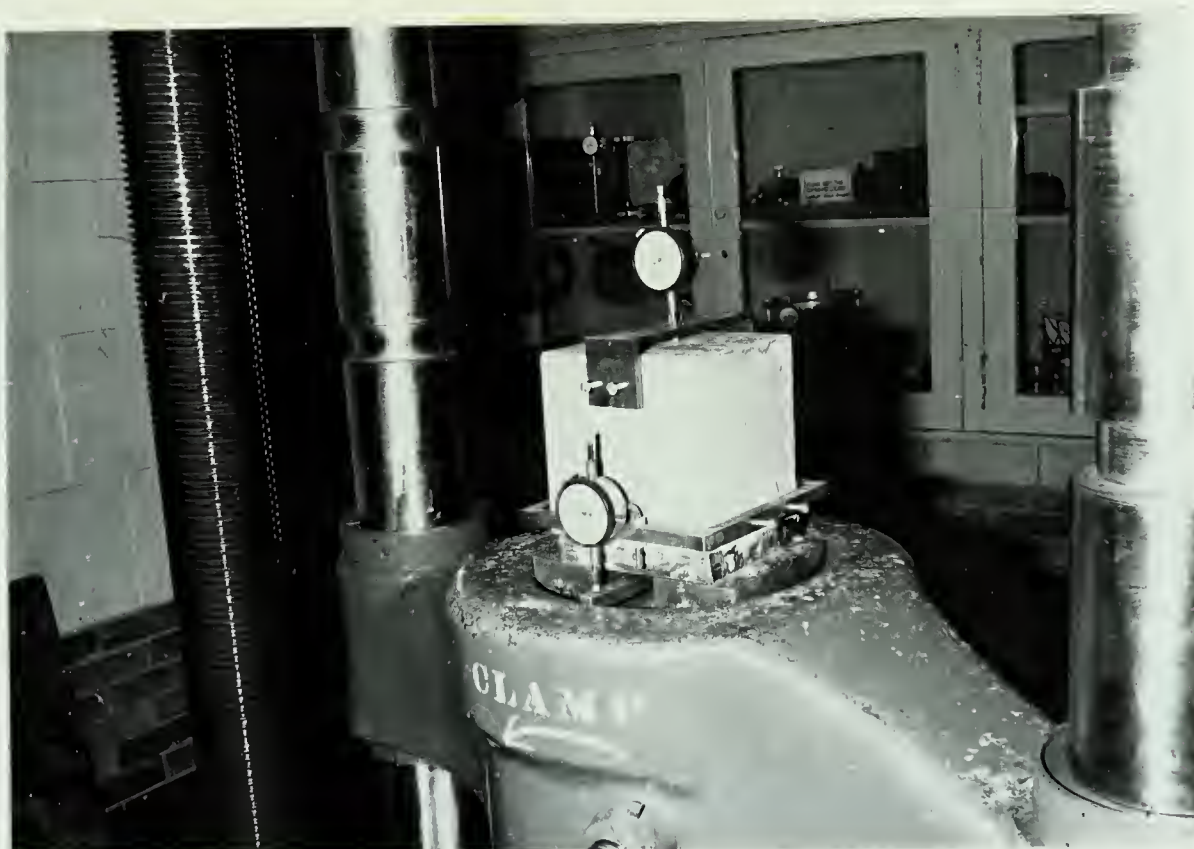


FIGURE 3

SLIP MEASUREMENT OF A.S.T.M. TEST

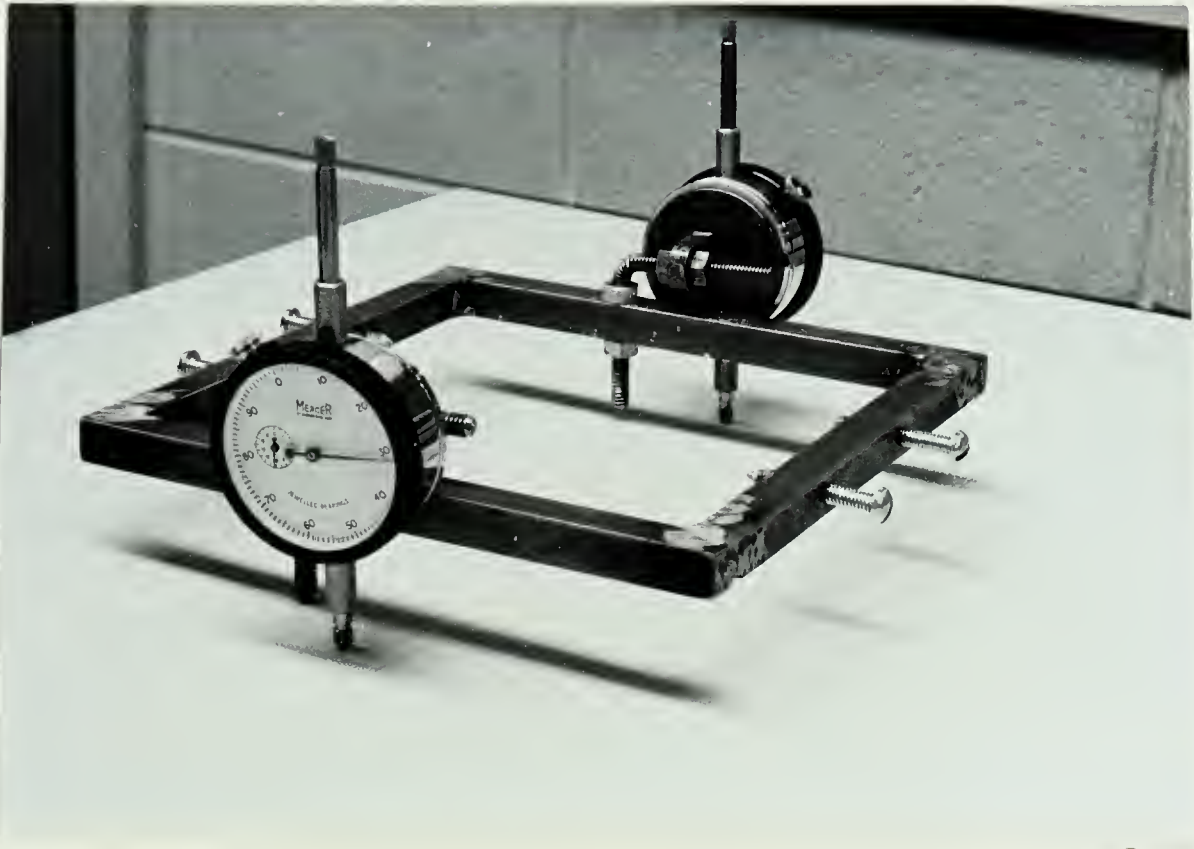


FIGURE 4

LOADED END SLIP MEASURING DEVICE

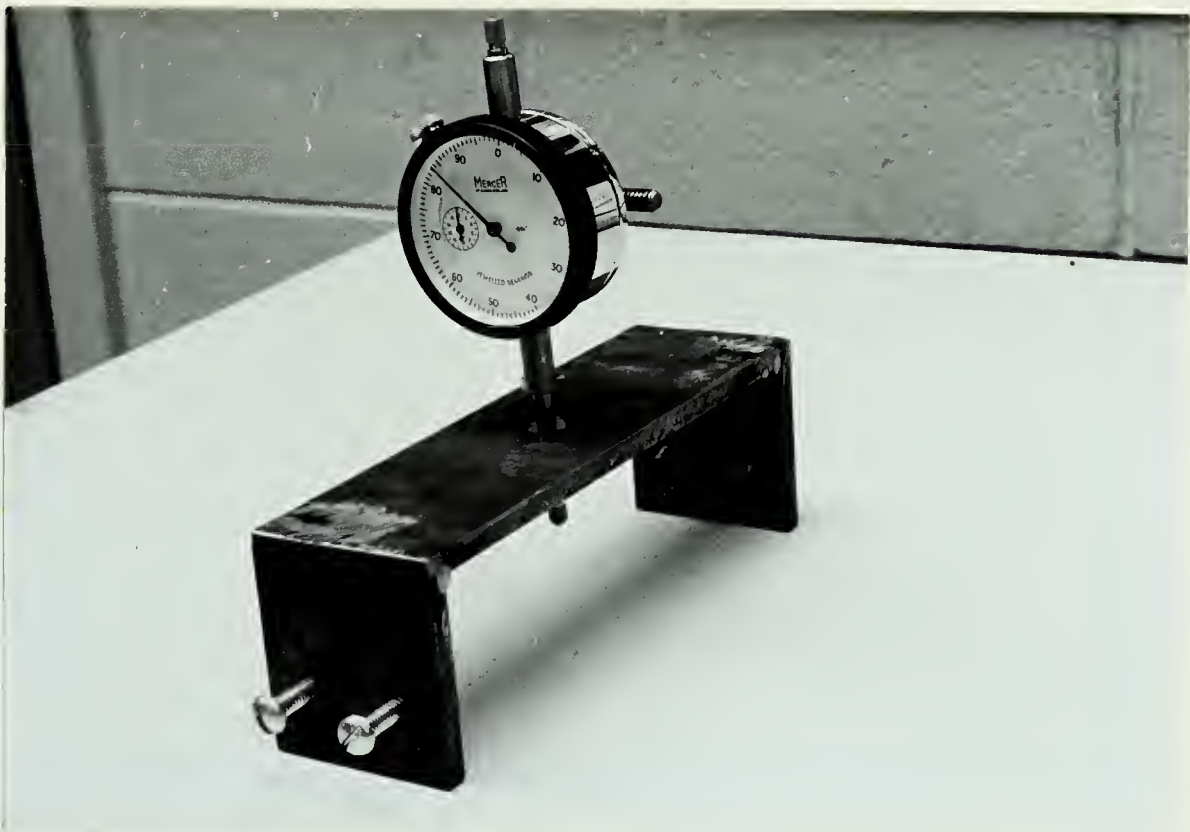


FIGURE 5

UNLOADED END SLIP MEASURING DEVICE

at the loaded end of the bar. This was clamped to the lower end of the specimen using the four screws shown. The dial gauges rested on a yoke previously attached to the reinforcing bar by means of small screws. FIGURE 5 shows the device for measuring slip at the unloaded end of the bar. This was clamped to the top of the specimen using four screws. The dial gauge rested on the exposed end of the embedded reinforcing bar.

Load was applied to the reinforcing bar in increments, with slip measurements taken at each increment. After yielding of the bar, slip measurements were discontinued because the yoke attached to the bar loosened, and further measurements were not reliable. Loading continued until the maximum load on the bar was attained. This was recorded as the failure load.

3. Spiral Reinforced Cylinder Pull-out Tests

A. Fabrication

These specimens were cast in 6 inch diameter by 12 inch long steel cylinder molds. The specimens were fabricated in the same framework used for the A.S.T.M. Tests, shown in FIGURE 1. The cylinder specimens are the first and third from the left end of the framework.

Before casting the concrete, the bar was centered in the mold containing a pre-formed wire spiral extending the full depth of the cylinder. The bar was set at the required embedment length and was clamped to the framework. Concrete was placed in the mold in three

layers and tamped a minimum of 25 times per layer, sometimes more if the concrete was difficult to compact around the spiral. The remainder of the fabrication details were similar to those for the A.S.T.M. Test.

B. Testing

Testing was identical to the A.S.T.M. Test procedure, except that no slip measurements were taken at the unloaded end, as this end of the bar was always embedded in the concrete. FIGURE 6 shows the specimen in the testing machine ready for testing.

4. Block Pull-out Tests

A. Fabrication

The first tests were conducted on #6 bars embedded in a large block of concrete 2'-0" square and 1'-0" deep. The bar was embedded in the center of the 2'-0" square face. In the latter stages of testing, when shorter embedment lengths were used, it was found that the concrete around the bar was affected in only a small area directly adjacent to the bar. This fact was utilized to save fabrication time. A larger 3'-6" square block, 1'-0" deep, was used to test both #3 and #6 bars. A #6 bar of short embedment length was cast in the concrete in the center of the 3'-6" square face, and one #3 bar was placed on each of three diagonals, 18 inches from the #6 bar, making a total of 4 bars in the same block. Only three #3 bars were used in each block because only 3 different embedment lengths



FIGURE 6

TESTING OF SPIRAL REINFORCED CYLINDER PULL-OUT TEST

were used for these bars.

The fabrication of both sizes of blocks was carried out in a similar manner. Both were cast in plywood forms. The forms were made adjustable so one set could accommodate both sizes of blocks. Dexion angles were used to hold the forms together and provide a framework to support the reinforcing bars during casting. The angles were bolted to the plywood to facilitate easy removal of the forms. The form for the 2'-0" square block is shown in FIGURE 7 and for the 3'-6" square block is shown in FIGURE 8. In both figures, the concrete was already placed in the forms.

The reinforcing bars were supported at the required height during casting by clamping them to the framework. The embedment lengths were 8", 6", 4" and 2" for the #6 bars, and 4", 2" and 1" for the #3 bars. For each embedment length, four different concrete mixes were used, giving companion tests for the A.S.T.M. and Spiral Reinforced Cylinder Pull-out Tests. No additional reinforcement was added to the concrete to provide additional strength or crack control.

Concrete was then placed in the forms using two methods. For the smaller blocks, one batch was used for the entire series of specimens. For the larger blocks, two batches were required. The first batch filled the form half full, but did not reach the bars. The next batch was sufficient to fill the remainder of the form, and also provide concrete for the other tests. Compaction was attained by vibrating with a small, electrically operated rod type vibrator. After vibration,

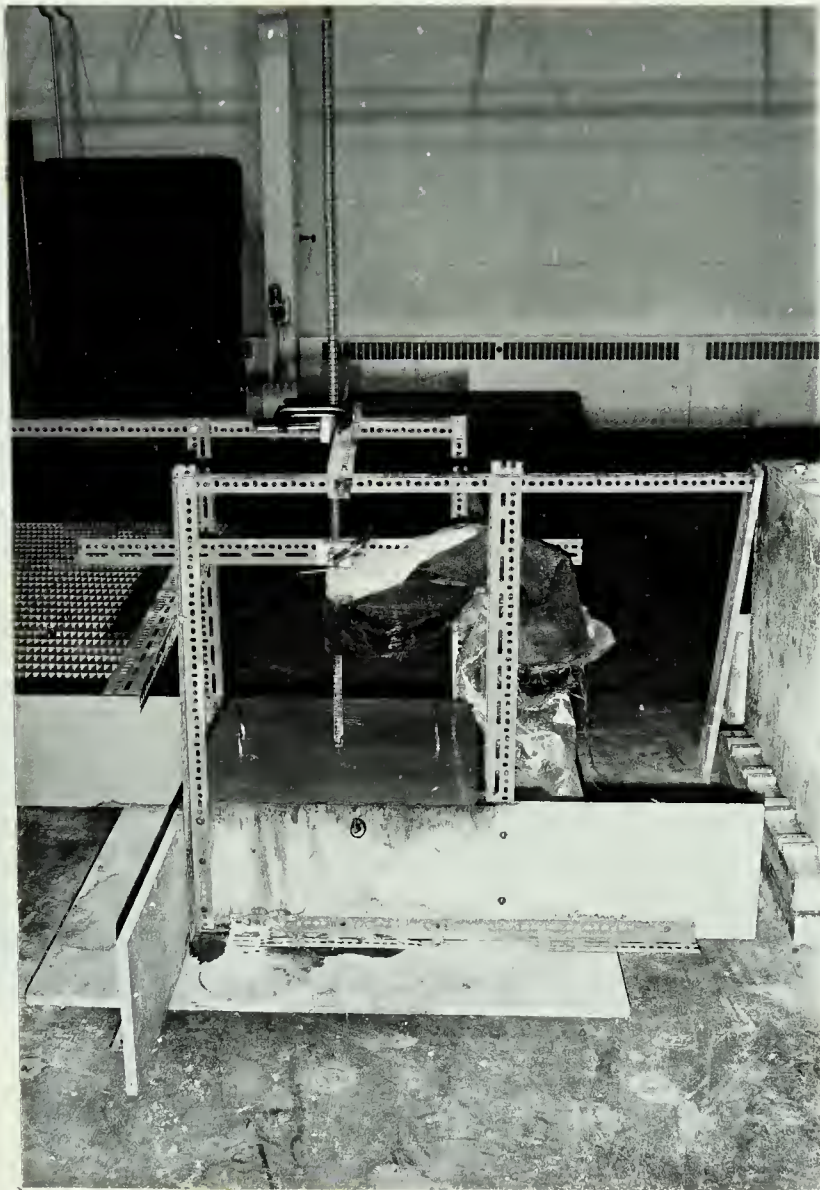


FIGURE 7

SMALLER BLOCK PULL-OUT SPECIMEN



FIGURE 8

LARGER BLOCK PULL-OUT SPECIMEN

the surface adjacent to the bar was finished carefully to ensure the proper embedment length. Lifting hooks were then placed near the edges of the block to facilitate removal of forms. A short 2 inch length of Dexion angle was embedded in the concrete 5 inches from the reinforcing bar to provide a platform for a magnetic base which supported a dial gauge used for slip measurements. Curing with wet burlap and polyethylene sheet was similar to the other specimens.

B. Testing

Testing was conducted on the seventh day after fabrication. The wet burlap and polyethylene were removed and the specimen allowed to dry out for about one hour before testing began. A general view of the testing apparatus is shown in FIGURE 9 and details of the testing frame are shown in FIGURE 10. The load was applied to the reinforcing bar by means of a 30-ton center-hole hydraulic jack bearing against a chuck placed on the bar. The load was transferred to the corners of the block using the frame shown. The loading and load measuring apparatus is shown in FIGURE 11. A 10-ton capacity load cell was placed between the jack and chuck to record the load on the bar.

The loading frame was assembled prior to testing, then lowered onto the pull-out specimen by an overhead crane. Before lowering the frame, a layer of Plaster-of-Paris was placed on each corner of the block to provide an even bearing surface for the frame base plates.

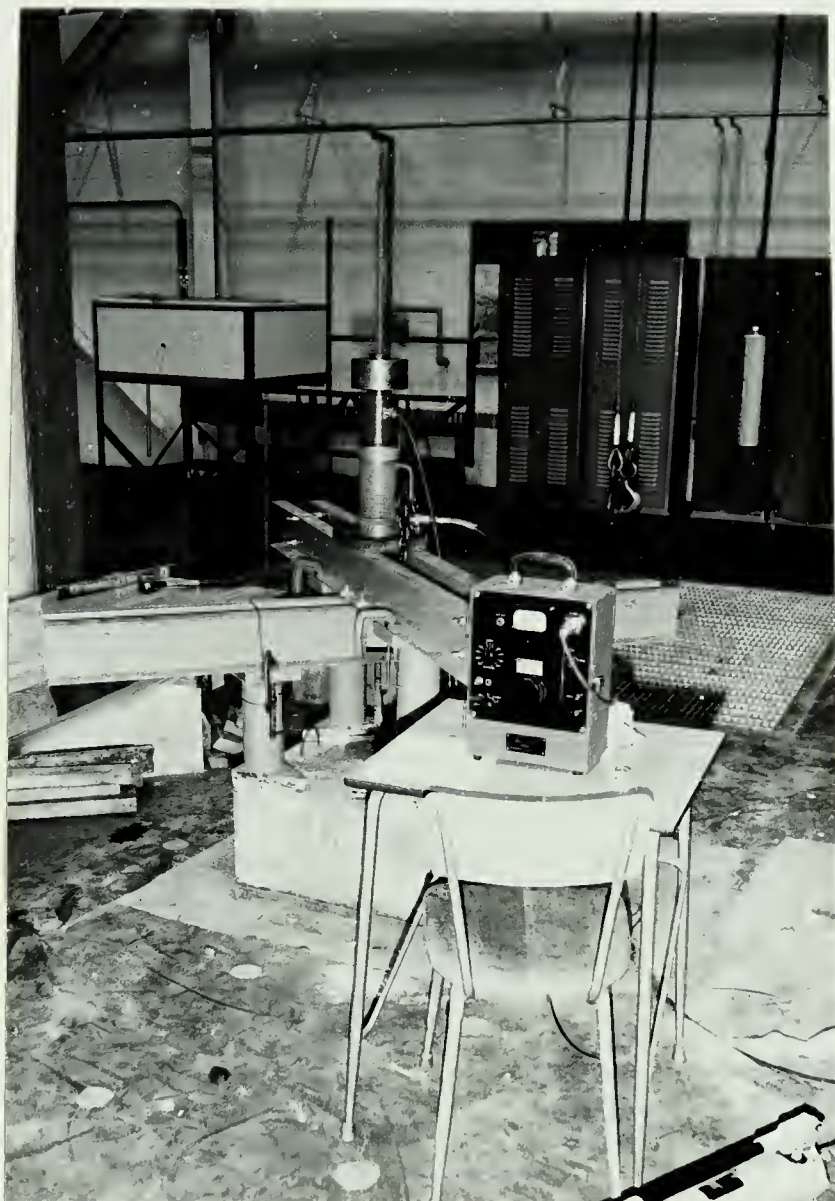


FIGURE 9

BLOCK PULL-OUT TESTING APPARATUS

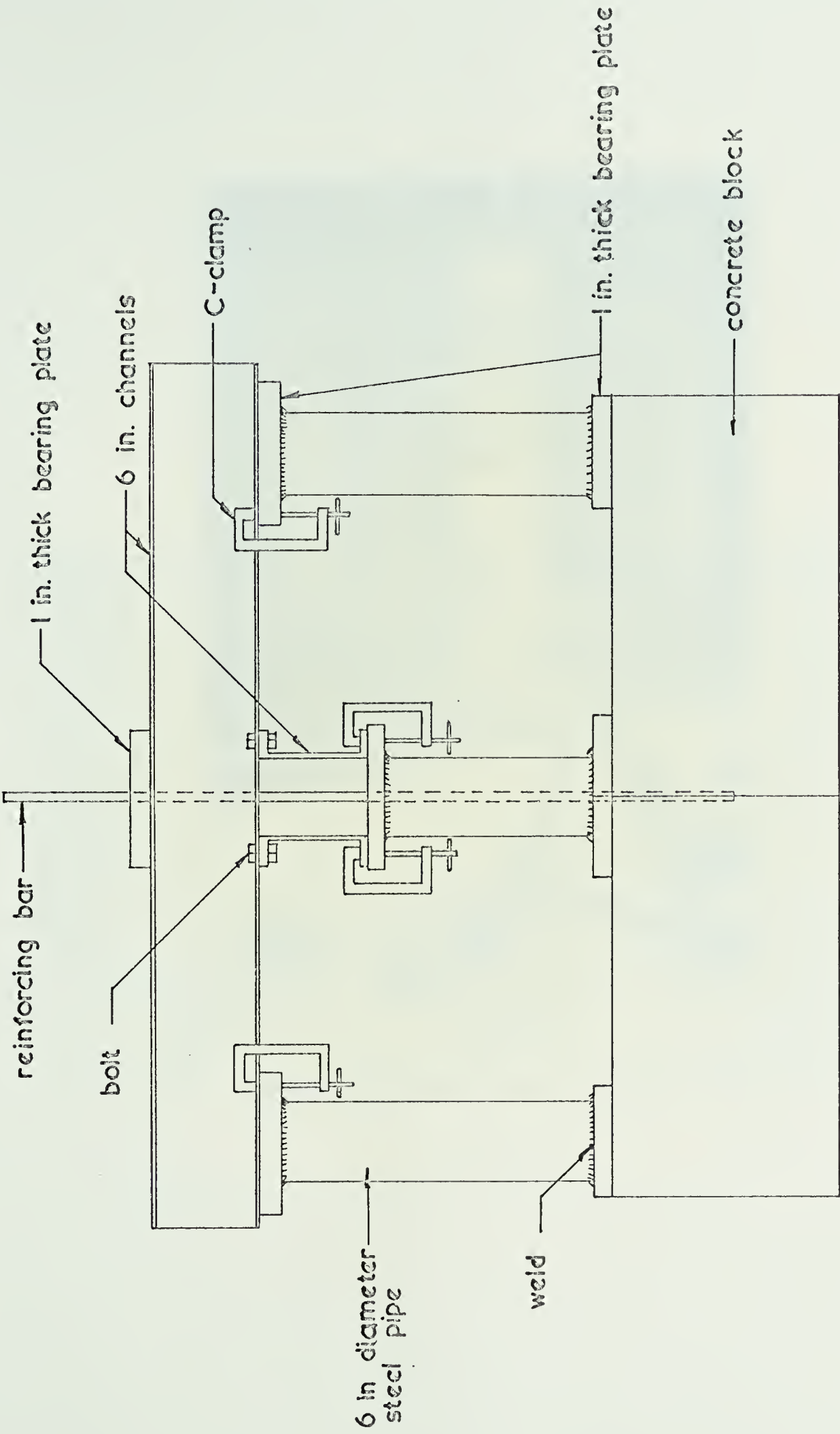


FIGURE 10 BLOCK PULL-OUT TESTING APPARATUS

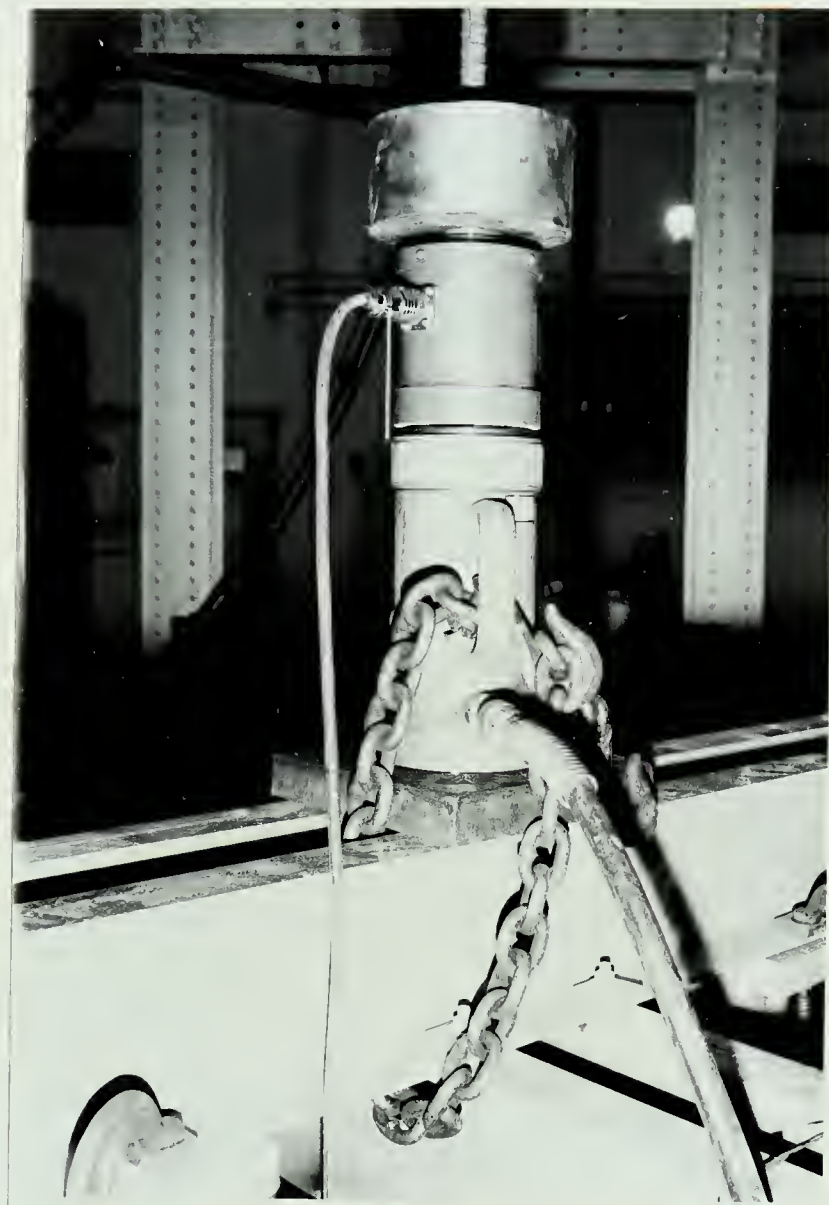


FIGURE 11

LOADING DEVICE FOR BLOCK PULL-OUT TEST

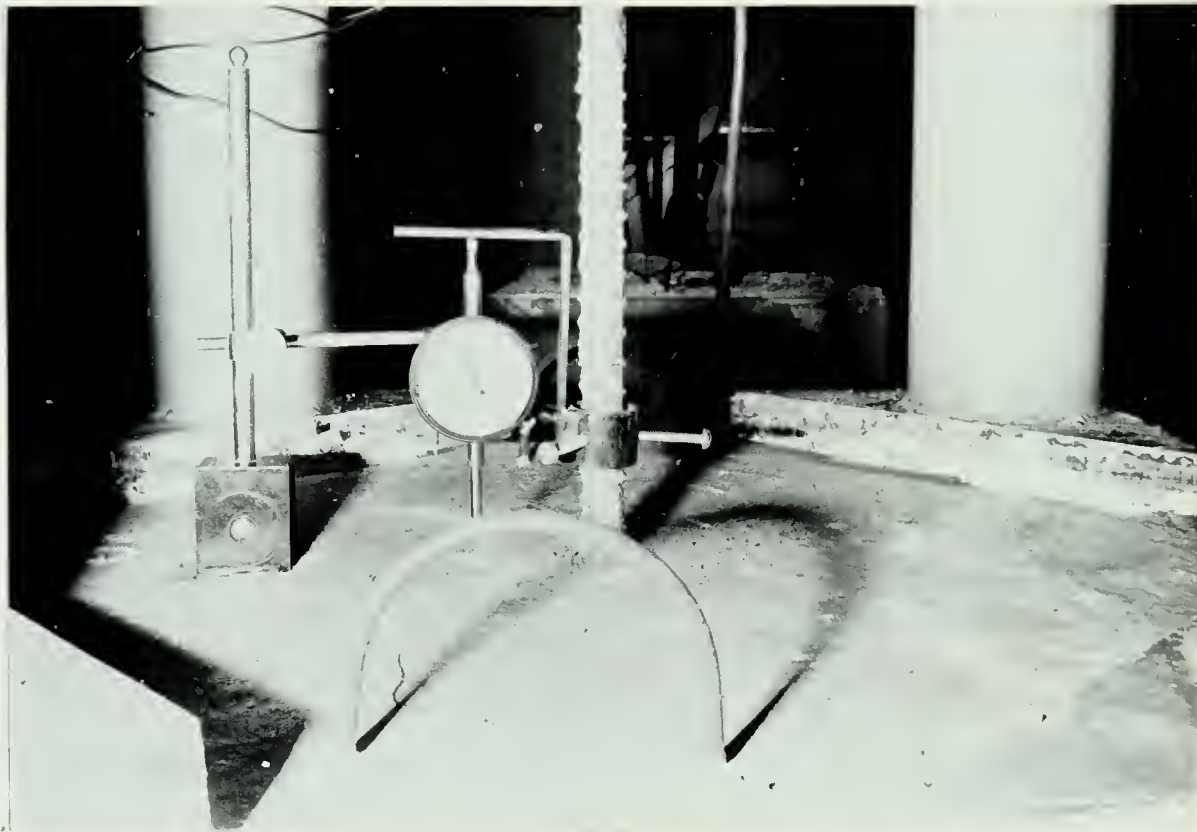


FIGURE 12

SLIP MEASURING DEVICE FOR BLOCK PULL-OUT TEST

Load was applied in increments to the bar using a hand operated hydraulic pump. Slip readings were taken at each increment using the apparatus shown in FIGURE 12. After yielding of the bar, slip readings were discontinued because the clamp became loose and reliable measurements could not be made. The load was increased until it reached a maximum and the bar pulled out of the concrete.

CHAPTER VII

RESULTS

1. General Remarks

The most important results observed were the ultimate values of bond resistance based on the actual maximum load attained during testing. Slip measurements, as will be shown later, were not very consistent, so ultimate bond resistance values based on excessive slip were not considered.

Each specimen was given a code number which designated all the pertinent information for that specimen. The code number consists of a letter followed by three numerals;

(1) The first letter indicates the type of specimen:

A represents the A.S.T.M. Pull-out Test.

S represents the Spiral Reinforced Cylinder Pull-out Test.

B represents the Block Pull-out Test.

(2) The second figure, or the first numeral, indicates the bar size, either #3 or #6.

(3) The next number indicates the embedment length in inches, ranging from 1 inch to 8 inches.

(4) The last number represents the approximate concrete compressive strength in k.s.i. to the nearest whole k.s.i.

An example would be B683. This means it is a Block Pull-out Test with a #6 bar embedded 8 inches in concrete of approximately 3 k.s.i. strength.

Because the range of concrete compressive strengths was quite large, it is of interest to compare the Modulus of Rupture and the Splitting Tensile Strength. This comparison is shown in FIGURE 13. The points appear to follow a straight line, so a mathematical average of all the points was used to establish a relationship. Using an equation based on the method of least squares, an unrealistic value of Modulus of Rupture resulted when the Splitting Tensile Strength was zero, so the mathematical average was used. The average of the results is given by Equation 3.

$$R = 1.49 T \quad (3)$$

The largest departure between the actual points and the equation is 35%, but the remainder of the points fall within about 10%, which is quite reasonable.

The results of the A.S.T.M. Tests are discussed first to illustrate the relationship used for reducing the remaining tests to a common concrete strength for comparison.

2. A.S.T.M. Pull-out Tests

TABLE IV shows the results of the A.S.T.M. Pull-out Tests. The values under the heading Reduced Ultimate Bond Resistance are

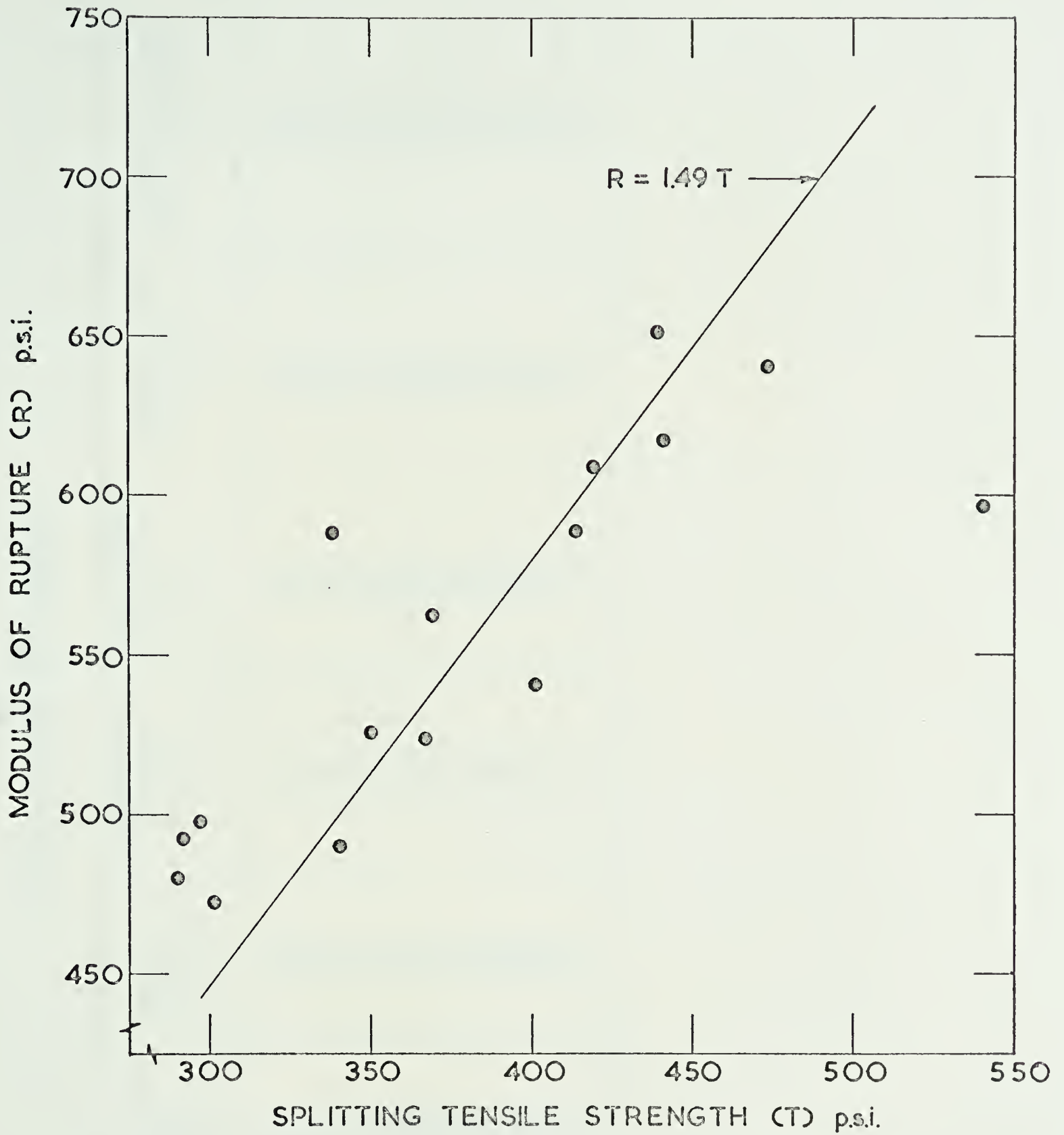


FIGURE 13 MODULUS OF RUPTURE
vs. SPLITTING TENSILE STRENGTH

TABLE IV

A.S.T.M. PULL-OUT TEST RESULTS

Specimen Number	Compressive Strength f_c' (p.s.i.)	Modulus of Rupture R (p.s.i.)	Splitting Tensile Strength T (p.s.i.)	Bond Stress at Yielding of Bar (p.s.i.)	Ultimate Bond Resistance (p.s.i.)	Reduced Ultimate Bond Resistance (p.s.i.)
A663	3340	480	290	1733	1970	2235
A664	3900	490	341	1737	2016	2120
A665	4875	610	419	1691	2271	2150
A665	5280	618	441	1694	2440	2200
A663	3145	472	301	1673	1797	2070
A664	3960	563	369	1669	1988	2090
A664	4395	541	401	1694	2280	2270
A666	5885	652	438	1680	2578	2210
A663	2780	493	292	1698	1720	2150
A664	3695	526	350	1769	2050	2220
A665	5080	589	413	1691	1980	1840
A666	6220	641	473	1708	2430	2030

the ultimate bond resistance values multiplied by a factor $\sqrt{\frac{f_c' \text{ average}}{f_c'}}$ where f_c' is the strength for that particular test, and f_c' average is the average strength of the entire group of tests. This was based on the procedure used in previous work, especially by Ferguson and Thompson (1962 and 1965) and further verification of this procedure is shown later in this chapter. The value of f_c' average was 4350 p.s.i.

A complete table of concrete mixes and strengths is in TABLE III, page 20.

Since all the A.S.T.M. Tests had the same bar size and embedment length or the same L/d ratio, a relationship between ultimate bond resistance and concrete strength can be developed. If the reduced ultimate bond resistance is plotted against concrete strength, a straight line should result if ultimate bond resistance varies as $\sqrt{f_c'}$. Such a plot is shown in FIGURE 14. All the points fall reasonably close to a straight line of 2.135 k.s.i., the average of the reduced ultimate bond resistances. The largest single variation from the average is about 16% while the remainder of points vary considerably less.

This is good verification of the relationship between ultimate bond resistance and f_c' and is further justification for reducing ultimate bond resistance to a common concrete strength for comparison.

The ultimate bond resistance for the A.S.T.M. Tests can be related to f_c' by:

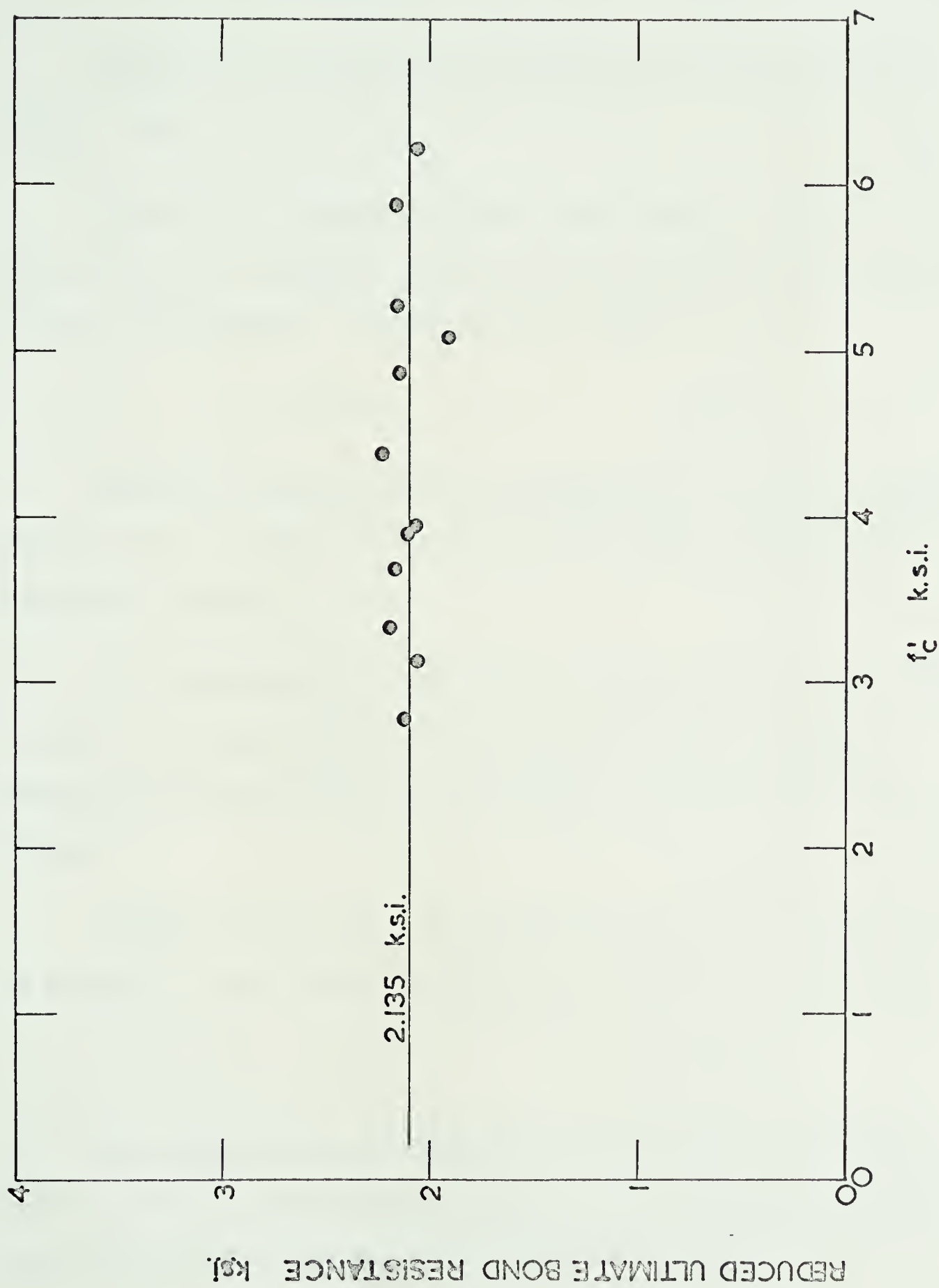


FIGURE 14 REDUCED ULTIMATE BOND RESISTANCE vs. f'_c FOR A.S.T.M. TESTS

$$u = 32.4 \sqrt{f_c'} \quad (4)$$

Equation 4 was determined by averaging the results of all the A.S.T.M. Tests.

FIGURE 15 is a graph of Ultimate Bond Resistance versus Splitting Tensile Strength, T , and the plotted points seem to indicate a linear relationship. The best fitting straight line is:

$$u = 5.67 T \quad (5)$$

Equation 5 was determined by averaging the results of all the A.S.T.M. Tests. Again, the method of least squares resulted in an unrealistic equation.

The largest departure between the actual points and the equation is 19%, most being within about 5%, which indicates a reasonable relationship between Ultimate Bond Resistance and Splitting Tensile Strength.

FIGURE 16 shows a plot of Ultimate Bond Resistance versus Modulus of Rupture, R . The equation determined from the arithmetic mean is:

$$u = 3.81 R \quad (6)$$

The largest departure between the equation and the plotted points is 16% with the remainder of points within this, but not as close as the relationship with the Splitting Tensile Strength.

The final mode of failure of all specimens was by splitting of

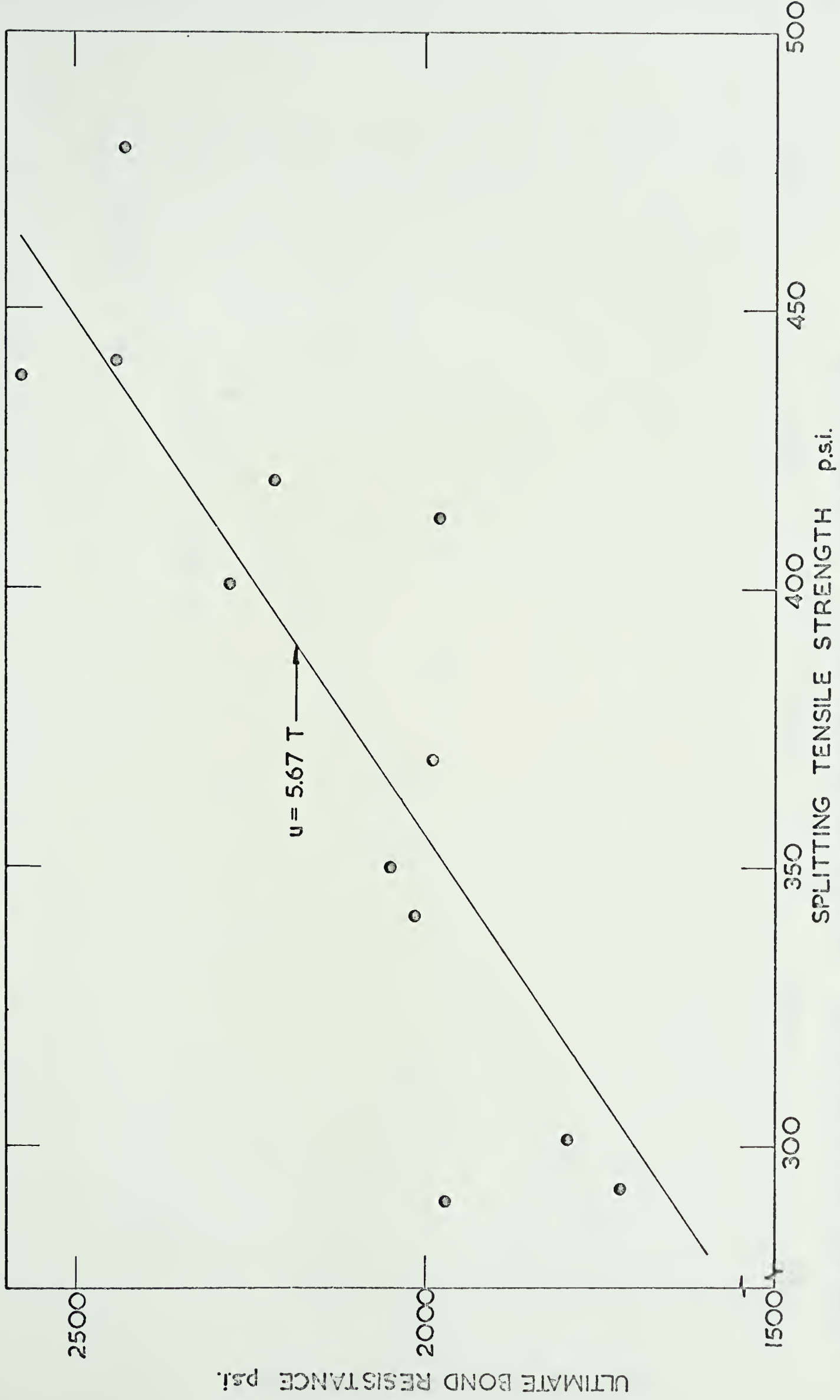


FIGURE 15 ULTIMATE BOND RESISTANCE VS. SPLITTING TENSILE STRENGTH FOR A.S.T.M. TESTS

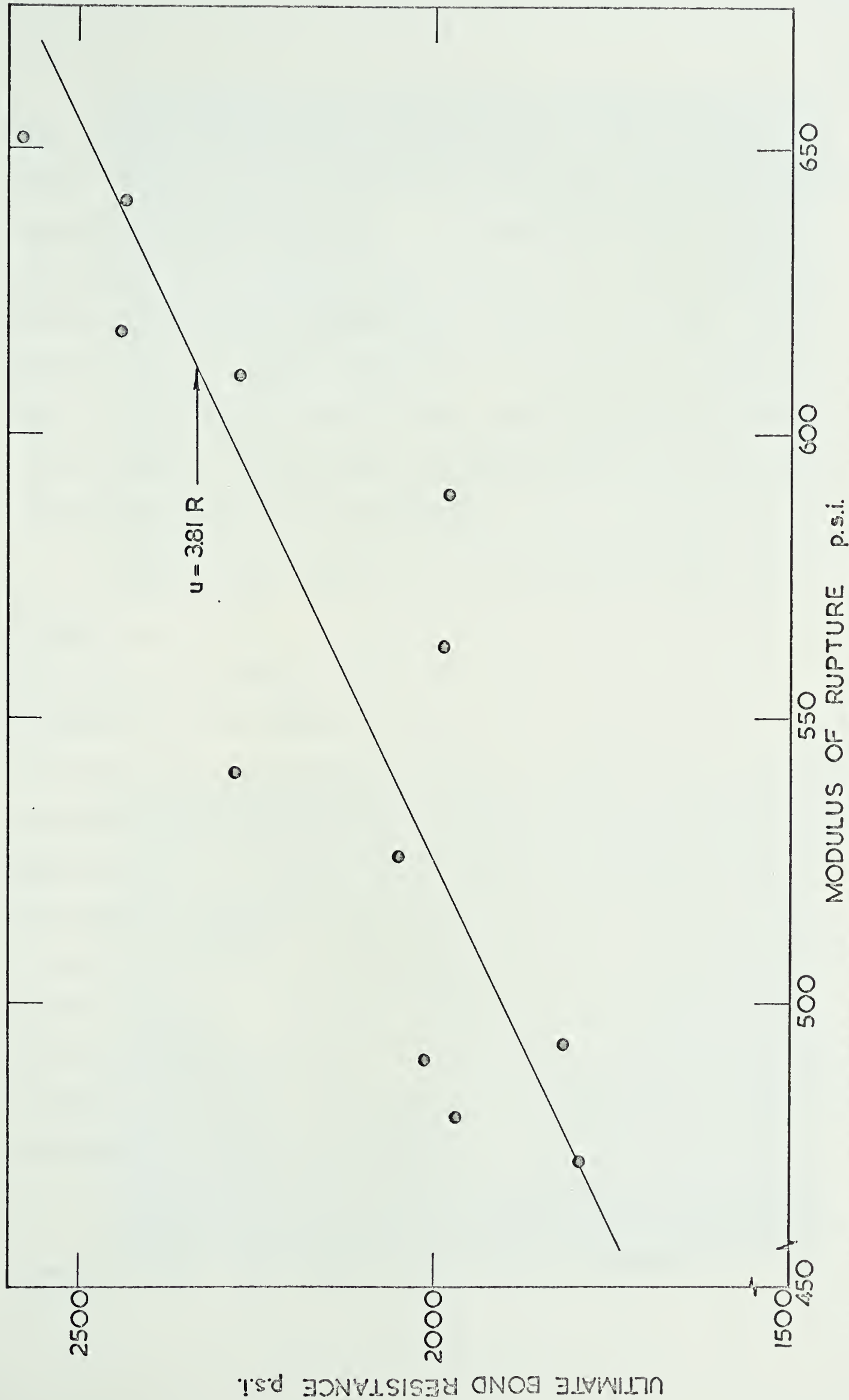


FIGURE 16 ULTIMATE BOND RESISTANCE VS. MODULUS OF RUPTURE FOR A.S.T.M. TESTS

the concrete surrounding the reinforcing bar. FIGURE 17 shows a typical failure with the cube splitting the entire length of the block parallel to the axis of the bar. In FIGURE 18, the cube is opened, showing the failure surfaces. The concrete between the deformations of the reinforcing bar appeared to be crushed in most cases. Upon failure, the bar slipped a large amount at the free end. This was due to elastic strain recovery in the reinforcing bar upon splitting of the concrete. In most cases, this slip was about $1/8$ inch, and occurred the instant the specimen split.

FIGURE 19 shows results of slip measurements taken at the loaded end of the bar. It must be noted that these curves are for slip only up to yielding of the reinforcing bar. Each curve is identified by the compressive strength of the concrete, rather than its code number. Curves for the 4875 p.s.i. and 3340 p.s.i. strength concretes were not smooth curves, probably because of friction in the measuring device. A broken line is shown for the probable curve. The bond-slip curves for concrete strengths above 3145 p.s.i. fall very close together. Only the curves for very low concrete strengths exhibit large slips. For most concrete strengths, it appears there is no appreciable difference in the bond-slip characteristics, therefore comparison of the slip curves for the other tests should be made without any adjustments for concrete strength.

FIGURE 20 shows a plot of Bond Stress versus Slip at the Free End of the Bar. There does not seem to be as consistent a

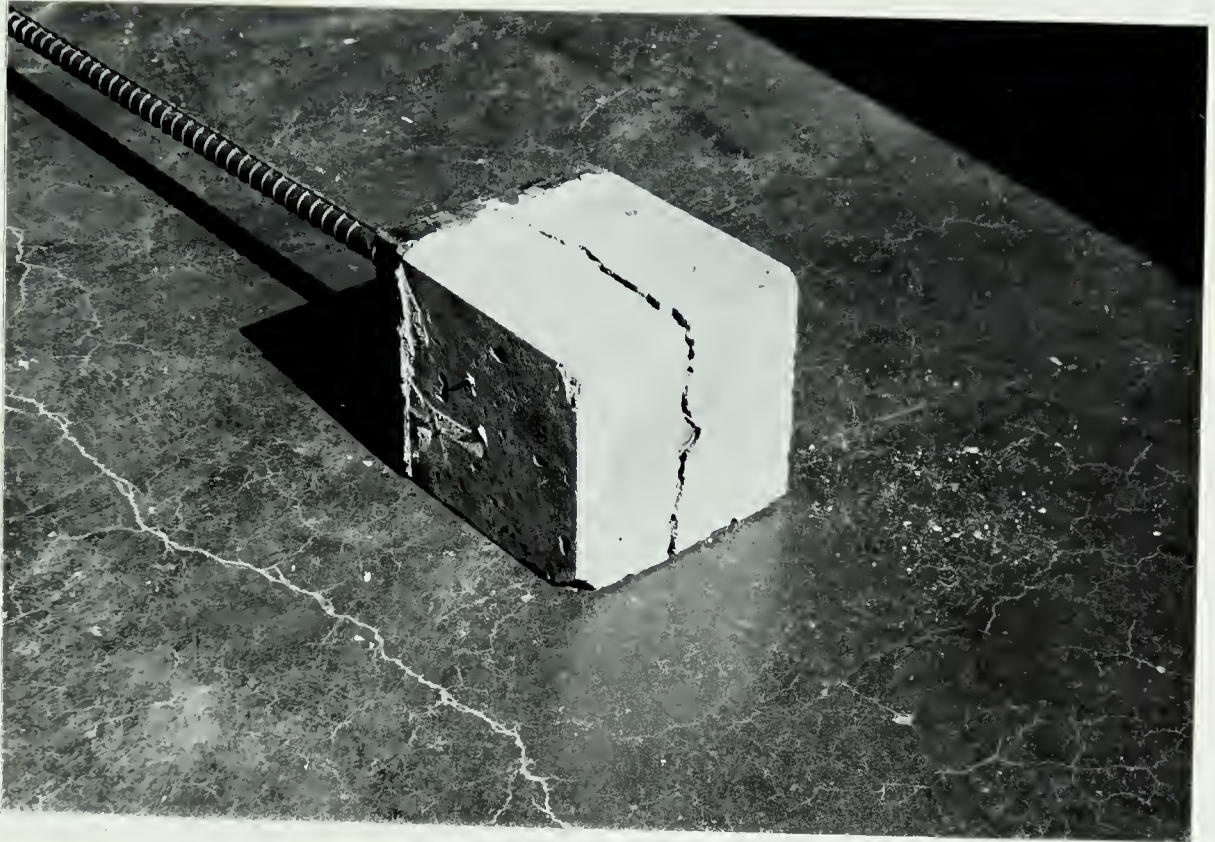


FIGURE 17

TYPICAL FAILURE OF A.S.T.M. TEST

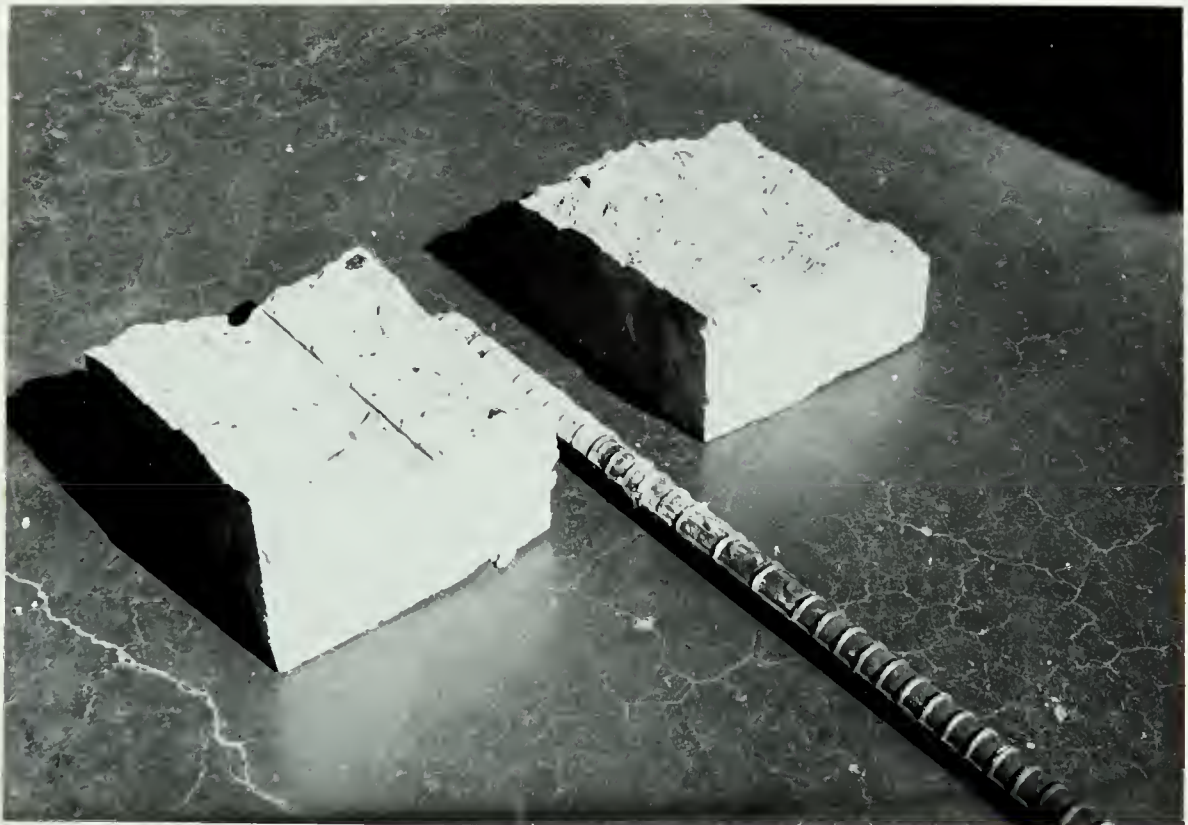


FIGURE 18

TYPICAL FAILURE OF A.S.T.M. TEST

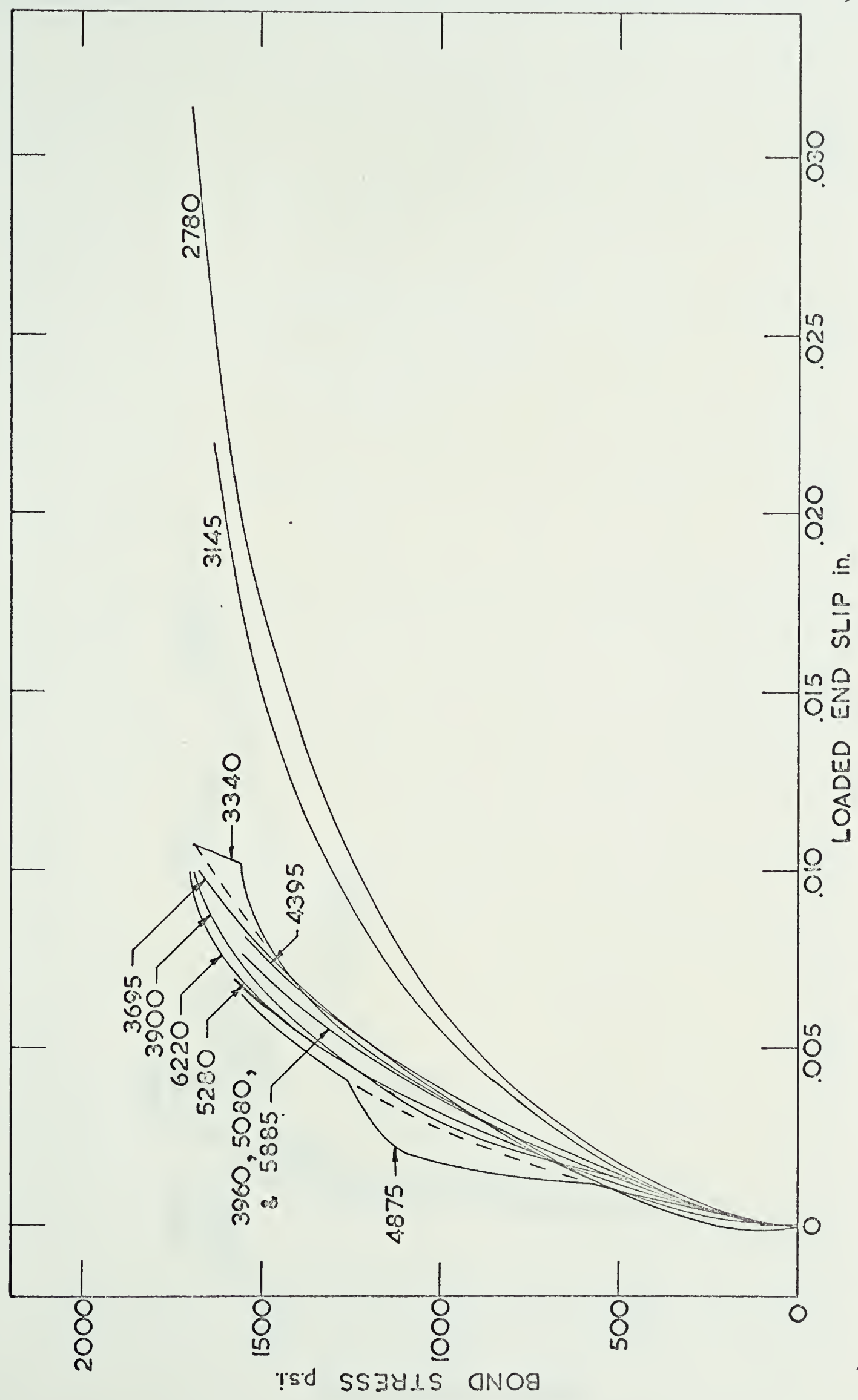


FIGURE 19 BOND STRESS vs. LOADED END SLIP FOR ASTM TESTS

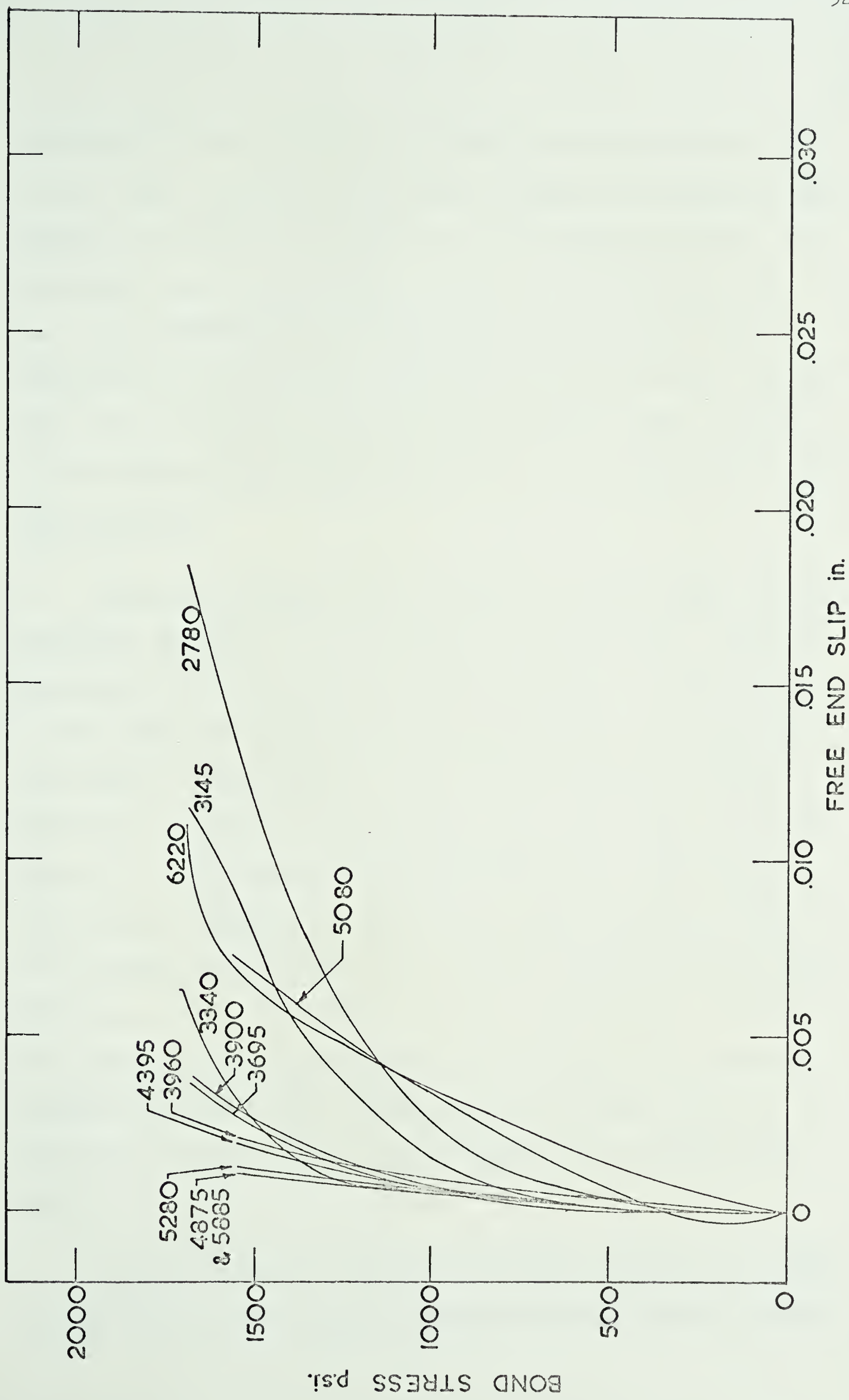


FIGURE 20 BOND STRESS vs. FREE END SLIP FOR ASTM. TESTS

relationship between Bond Stress and Slip as for the loaded end slip curves. Many of the curves are grouped together, but there are large amounts of slip shown for both low and high strength concretes. No explanation can be given for this behavior, except that there may have been a difference due to faulty fabrication of some of the specimens as a result of poor compaction near the free end of the bar. These curves cannot be used for comparison with the other specimens of the testing program because free-end slip was not measured on the other specimens.

The actual ultimate bond resistances were much higher than any previously reported for a similar type of pull-out test. The reason for this was that the previous results were based on excessive slip of the loaded end which would give a lower ultimate bond resistance. If a limit of loaded end slip of 0.01 inches is used as a failure criterion, the ultimate bond resistance would still range from about 1600 p.s.i. to 1700 p.s.i. as seen from FIGURE 19. This is greater than stresses reported, for example, by Untrauer and Henry (1965), for specimens with no normal stress. Their ultimate resistances were about 1200 p.s.i. The difference probably results from a different orientation of the reinforcing bar during casting of the specimen. Untrauer and Henry (1965) used horizontally cast bars which, as described previously, gives lower resistance than vertically cast bars.

Aside from the two exceptions previously mentioned, the loaded end and free end curves compare favorably for most concrete strengths.

3. Spiral Reinforced Cylinder Pull-out Tests

TABLE V shows the results of the Spiral Reinforced Pull-out Tests.

The ultimate bond resistances are reduced to a common concrete strength of 4350 p.s.i., by the same method used for the A.S.T.M. Tests to check if the ultimate bond resistance does vary as $\sqrt{f_c'}$. In most cases, this reduction seems justified, as the reduced ultimate bond resistances for the same L/d ratio are grouped relatively close together. The S64, S32, and S31 groups show an increase in reduced ultimate bond resistance with an increase in concrete strength. These trends are probably not significant, however, more tests in these groups would have to be conducted before any definite conclusion is drawn. For further comparisons, the ultimate bond resistance is assumed to vary as $\sqrt{f_c'}$.

A group of specimens with the same bar size and embedment length will be represented by a single ultimate bond resistance which is the average of the reduced ultimate bond resistances for that group.

The failure for this pull-out test was due to crushing of the concrete between the bar deformations, with possible shearing of the concrete between deformations near the loaded end. There was no cracking of the concrete at failure.

A plot of Reduced Ultimate Bond Resistance versus L/d was made

TABLE V
SPIRAL REINFORCED CYLINDER PULL-OUT TEST RESULTS

Specimen Number	Compressive Strength f_c' (p.s.i.)	Modulus of Rupture R (p.s.i.)	Splitting Tensile Strength T (p.s.i.)	Bond Stress at Yielding of Bar (p.s.i.)	Ultimate Bond Resistance (p.s.i.)	Reduced Ultimate Bond Resistance (p.s.i.)
S683	3340	480	290	1305	1830	2070
S684	3900	490	341	1295	1947	2050
S685	4875	610	419	1252	1945	1840
S685	5280	618	441	1694	Bar failed	Bar failed
S663	3145	472	301	1666	1914	2200
S664	3960	563	369	1666	2094	2190
S664	4395	541	401	1694	2385	2370
S666	5885	652	438	1677	2660	2290
S643	2780	493	292	1592	1655	2075
S644	3695	526	350	*	2190	2370
S645	5080	589	413	2536	2743	2540
S646	6220	641	473	2504	3348	2800
S623	2645	498	297	*	1921	2450
S624	4415	574	367	*	2600	2810
S625	4570	588	338	*	2886	2550
S626	5680	597	540	*	4213	3690
S343	2645	498	297	1210	1380	1770
S344	4415	574	367	1144	1719	1680
S345	4570	588	338	1199	1624	1580
S346	5680	597	540	1210	1804	1580
S323	2645	498	297	*	1507	1920
S324	4415	574	367	*	2271	2230
S325	4570	588	338	*	2250	2200
S326	5680	597	540	2419	3013	2640
S313	2645	498	297	*	1528	1960
S314	4415	574	367	*	2377	2330
S315	4570	588	338	*	2462	2400
S316	5680	597	540	*	5518	4830

* Indicates bar did not yield before failure.

to see if the tests conformed to previous results. This is shown in FIGURE 21. The curves show the same general trend, that is, a decrease in reduced ultimate bond resistance for an increase in the L/d ratio.

Previous investigators, such as Abrams (1913) and Mathey and Watstein (1961) found that for the same L/d ratio, ultimate bond resistance was larger for a smaller diameter bar. FIGURE 21 shows results contrary to these authors, that is, at least for an L/d ratio greater than about 3. The smaller bar shows a decrease in bond for the same L/d ratio. The reason for this is probably because the results shown in FIGURE 21 are for actual ultimate bond resistances, not those based on failure at a specified slip.

From figures shown later in this chapter, values of reduced ultimate bond resistance for a slip of 0.01 inches were plotted against L/d in FIGURE 22. This graph shows a closer relationship between the #6 and #3 bars. The ultimate bond resistance values for the #3 bar were very limited in that most of the specimens had amounts of slip which were less than 0.005 inches upon discontinuation of slip measurements. It is felt that if the bond-slip curves for the #3 bars were projected beyond a slip of 0.01 inches, the resulting curve in FIGURE 22 would indeed be above that for the #6 bar, which would coincide with works of previous authors.

The reason for the increase in ultimate bond resistance for the larger size bar with the same L/d ratio is not definitely known. The

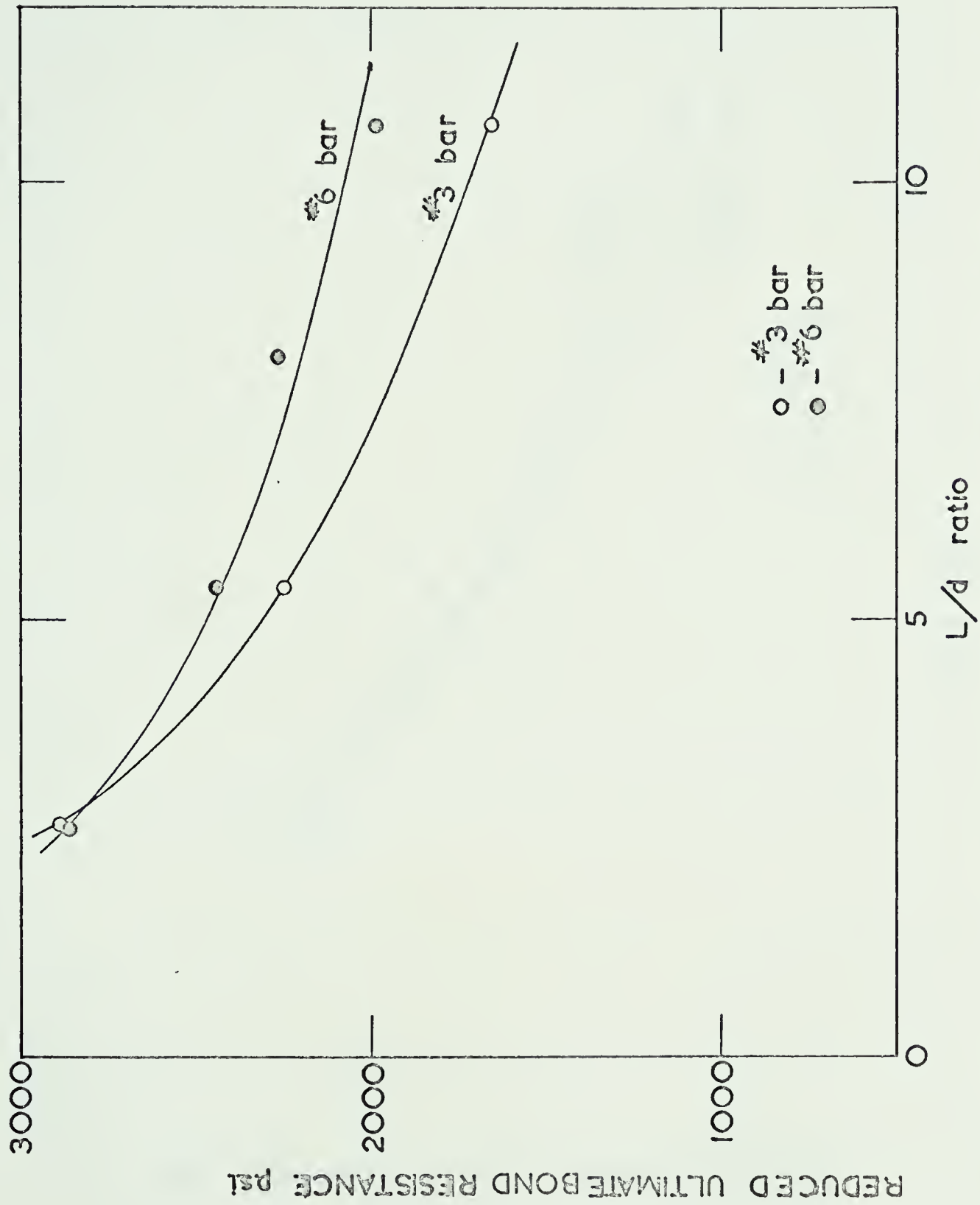


FIGURE 2I REDUCED ULTIMATE BOND RESISTANCE vs. L/d FOR SPIRAL REINFORCED CYLINDER PULL-OUT TESTS

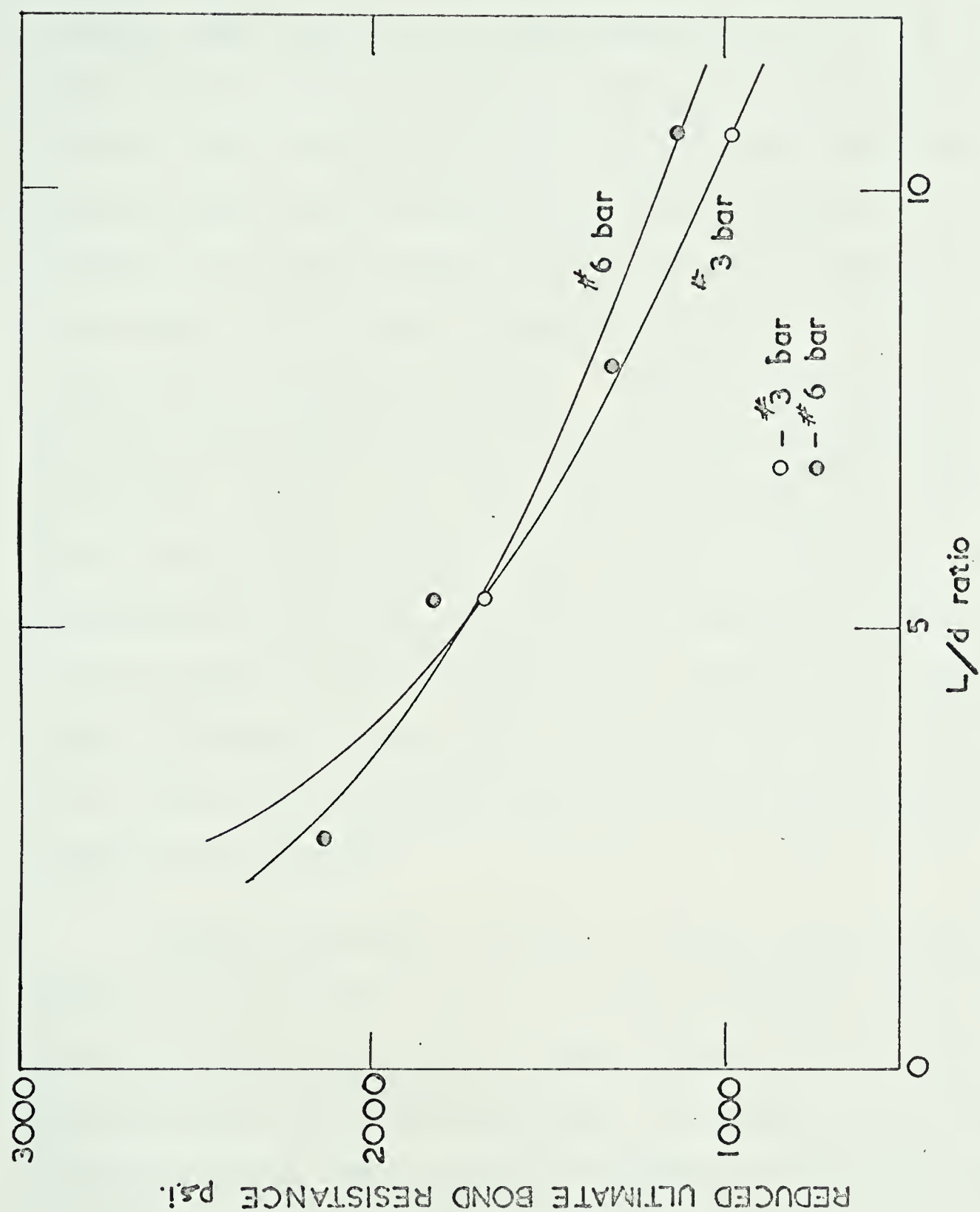


FIGURE 22 REDUCED ULTIMATE BOND RESISTANCE vs. L/d
BASED ON LOADED END SLIP OF 0.01 IN.

progression of bond failure may be a reason for this behavior. In the shorter, smaller bar, the bond stress is quite high over most of the embedded length, resulting in a high average bond stress. The high stress near the loaded end results in bond failure which progresses rapidly to the other end of the bar. In the longer, larger bar, the high bond stress near the loaded end initiates crushing of the concrete which still provides a relatively high bond resistance in this region. As the failure progresses towards the unloaded end, a higher stress develops near this end. Because of the length of embedded bar, the crushing failure does not allow as rapid a failure as in the shorter bar. This may give enough time for the stress near the free end to develop a much greater value than that for short bars. The combination of a very high stress near the unloaded end with a relatively high "residual" stress over the remainder of the bar, would result in a higher average ultimate bond resistance than for the short bar. Stress distribution measurements would have to be conducted to confirm this hypothesis.

Ferguson and Thompson (1962 and 1965) show that for beam tests, a plot of ultimate bond resistance versus the embedment length gives a continuous curve for all sizes of bars. A plot of Reduced Ultimate Bond Resistance versus Embedment Length, L , was made to see if similar behavior occurred. This is shown in FIGURE 23. As seen from FIGURE 23, the curves are separated more than those in FIGURE 21 where the L/d parameter was used.

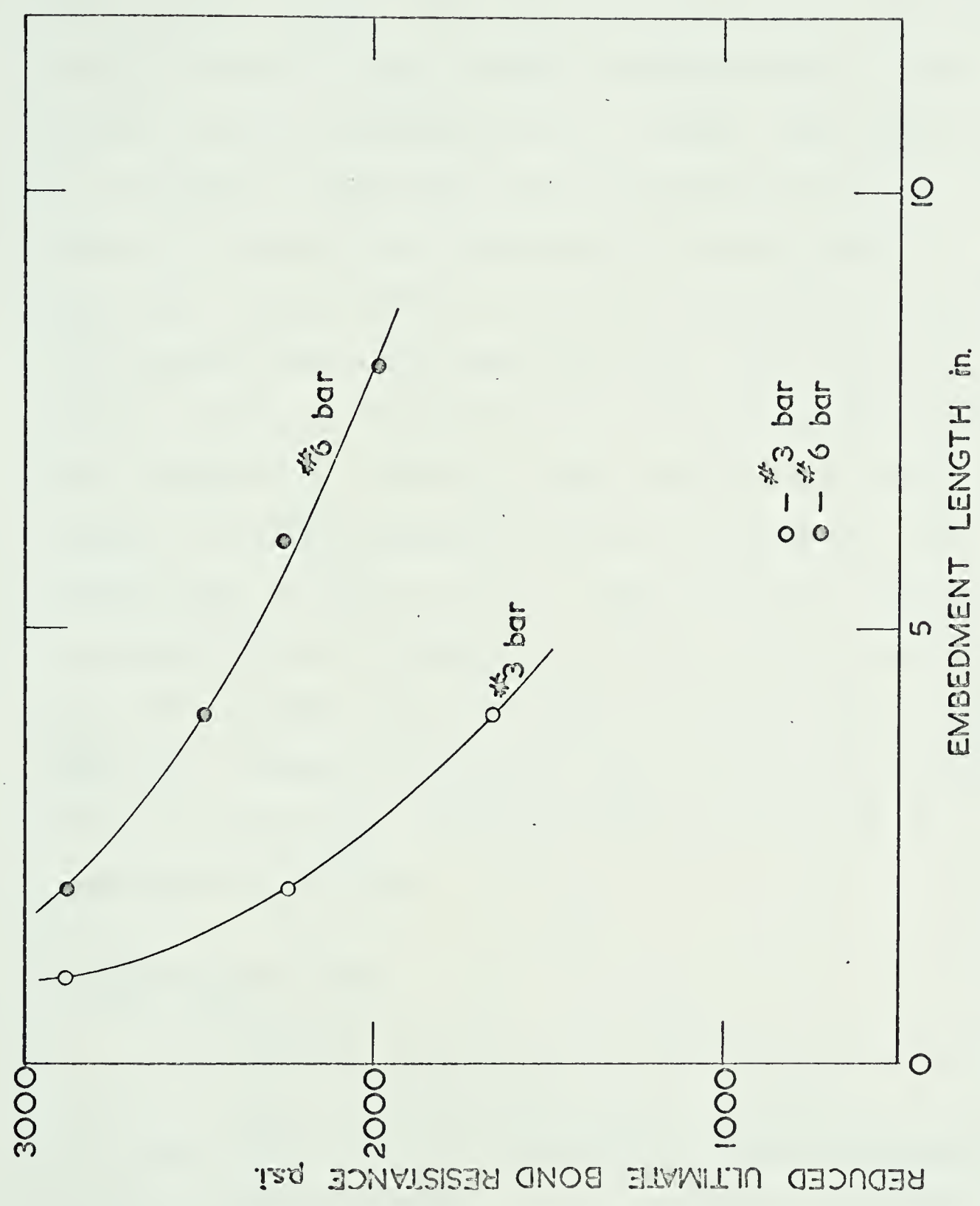


FIGURE 23 REDUCED ULTIMATE BOND RESISTANCE VS. EMBEDMENT LENGTH
FOR SPIRAL REINFORCED CYLINDER PULL-OUT TESTS

Curves for Bond Stress versus Loaded End Slip are shown for both sizes of bars. FIGURE 24 is for the #6 bars and FIGURE 25 is for the #3 bars. Some of the curves are quite erratic and no specific trend is indicated. Again it should be mentioned that slip was measured only until yielding of the bar occurred. The negative slip at low stresses for some tests cannot definitely be explained. This behavior is probably due to malfunction of the slip measuring apparatus. Improper seating of the device, or friction between parts of the apparatus may have caused these errors. From both of the figures, the only trend discernable is a rise in the bond-slip curves for a decrease in the embedment length, and also a rise for an increase in concrete strength for the same bar embedment. This indicates that if slip was used as a failure criterion, results of the relationships between ultimate bond resistance, concrete strength, and L/d would be somewhat similar to those using actual ultimate bond resistances. Because the bond slip curves were not very consistent, no attempt was made to use ultimate resistances based on slip for comparison with other tests.

4. Block Pull-out Tests

The results of the Block Pull-out Tests are shown in TABLE VI.

Again, the ultimate bond resistance is reduced to a common concrete strength of 4350 p.s.i. in the same manner as previous results. The reduced ultimate bond resistances did not vary greatly within a group with the same embedment length, indicating the reduction

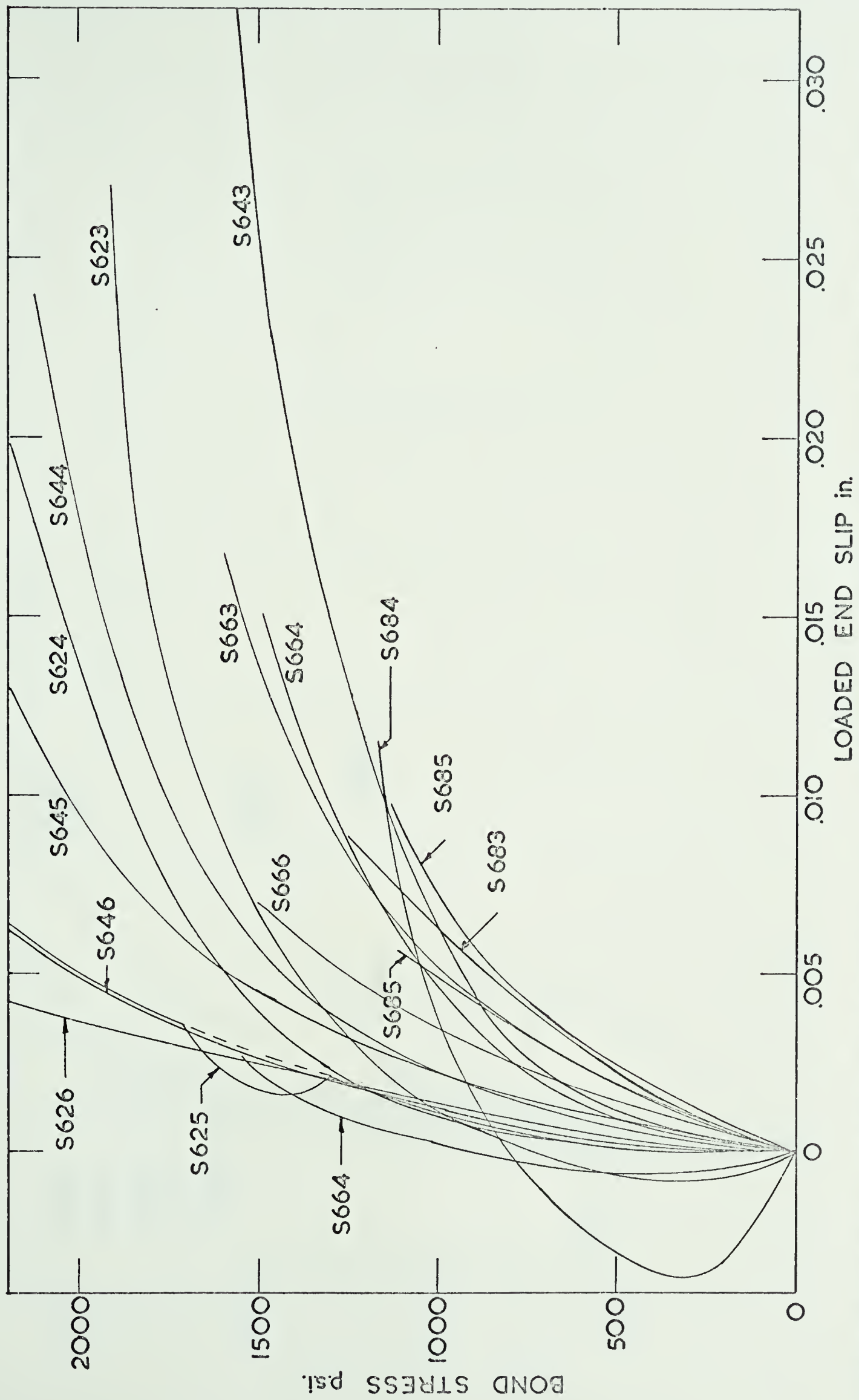


FIGURE 24 BOND STRESS VS. LOADED END SLIP FOR #6 BAR IN SPIRAL REINFORCED CYLINDER PULL-OUT TESTS

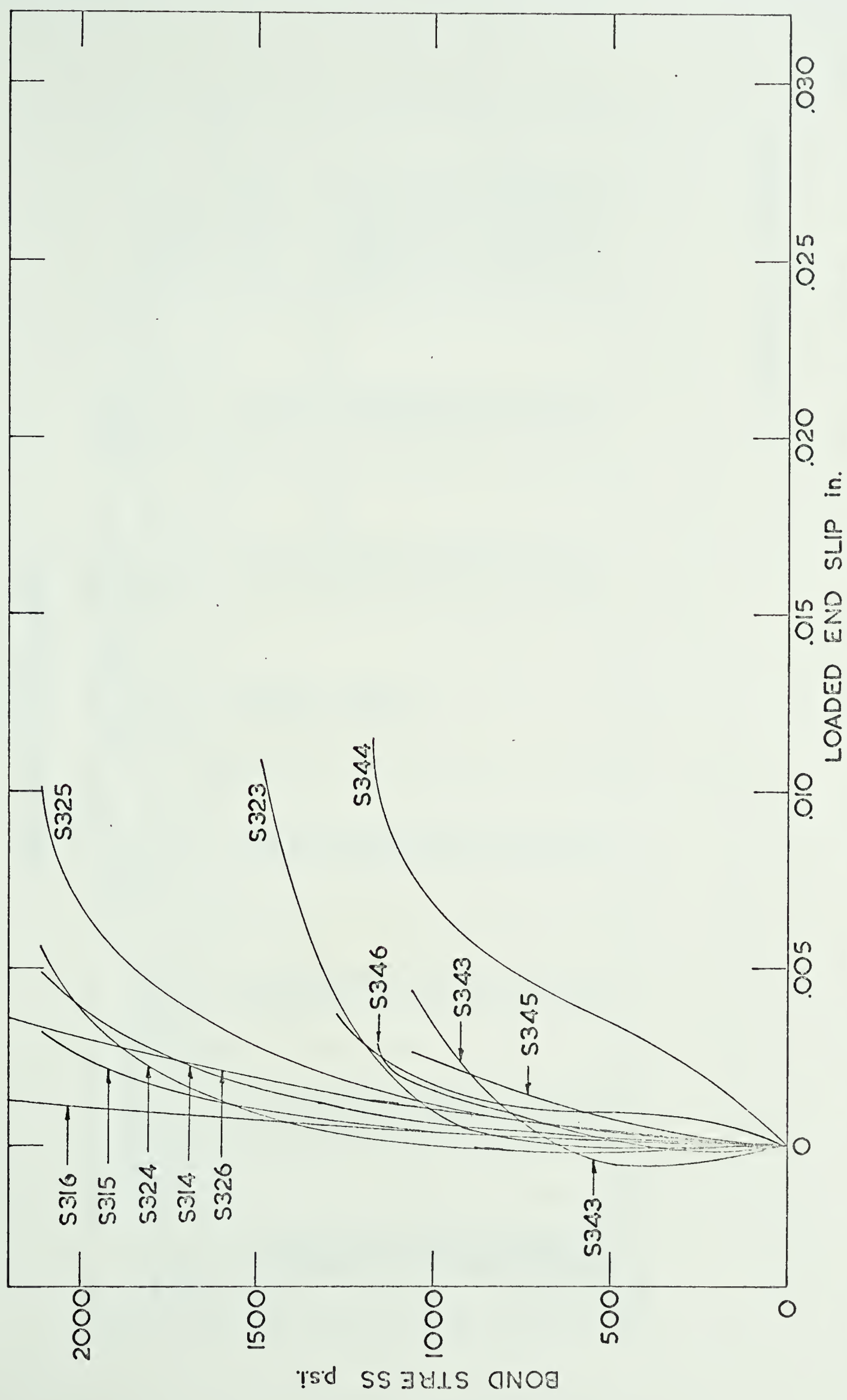


FIGURE 25 BOND STRESS vs. LOADED END SLIP FOR #3 BAR IN SPIRAL REINFORCED CYLINDER PULL-OUT TESTS

TABLE VI

BLOCK PULL-OUT TEST RESULTS

Specimen Number	Compressive Strength f_c' (p.s.i.)	Modulus of Rupture R (p.s.i.)	Splitting Tensile Strength T (p.s.i.)	Bond Stress at Yielding of Bar (p.s.i.)	Ultimate Bond Resistance (p.s.i.)	Reduced Ultimate Bond Resistance (p.s.i.)	Type of Failure*
B683	3340	480	290	1369	1486	1685	S, 24.0, 5.0
B684	3900	490	341	1337	1738	1830	B, 6.0, 1.5
B685	4875	610	419	1273	1878	1775	S
B685	5280	618	441	1273	Bar failed	Bar failed	R
B663	3145	472	301	+	1556	1790	B, 20.0, 4.0
B664	3960	563	369	1698	1705	1790	S, 12.0, 2.5
B664	4395	541	401	1719	1855	1850	B, 24.0, 4.0
B666	5885	652	438	1712	2415	2075	B, 10.0, 1.5
B643	2780	493	292	+	1010	1260	B, 10.0, 1.8
B644	3695	526	350	+	1540	1670	B, 15.0, 2.5
B645	5080	589	413	+	1800	1670	B, 16.0, 2.5
B646	6220	641	473	+	2065	1725	SH, 16.0, 4.0
B623	2645	498	297	+	1050	1340	B, 12.0, 2.0
B624	4415	574	367	+	1270	1240	B, 16.0, 1.8
B625	4570	588	338	+	1220	1200	B, 17.0, 2.0
B626	5680	597	540	+	1620	1420	B, 22.0, 2.0

...continued on next page

.....continued

TABLE VI
BLOCK PULL-OUT TEST RESULTS

Specimen Number	Compressive Strength f_c' (p.s.i.)	Modulus of Rupture R (p.s.i.)	Splitting Tensile Strength T (p.s.i.)	Bond Stress at Yielding of Bar (p.s.i.)	Ultimate Bond Resistance (p.s.i.)	Reduced Ultimate Bond Resistance (p.s.i.)	Type of Failure*
B343	2645	498	297	1210	1273	1630	B,6.0,1.0
B344	4415	574	367	1167	1634	1600	B,3.0,0.5
B345	4570	588	338	1188	1528	1490	B,5.0,0.5
B346	5680	597	540	1210	1740	1520	B,2.5,0.5
B323	2645	498	297	+	1061	1360	B,6.0,1.0
B324	4415	574	367	+	1761	1725	B,6.0,1.0
B325	4570	588	338	+	1761	1720	B,6.0,1.0
B326	5680	597	540	+	2419	2120	B,13.0,1.8
B313	2645	498	297	+	1230	1575	B,5.0,1.0
B314	4415	574	367	+	1401	1375	B,6.0,1.0
B315	4570	588	338	+	1401	1370	B,3.5,0.8
B316	5680	597	540	+	1570	1370	B,4.0,0.5

* First letter designates type of failure: S = Splitting
 B = Bond
 R = failure of bar
 SH = shearing of corners of blocks
 First number indicates diameter of "Tension Cone".
 Second Number indicates depth of "Tension Cone".

+ Indicates bar did not yield before failure.

is reasonably justified. It should be noted here that the failure was not completely a bond failure, but was influenced by tensile failure of the concrete. However, for further comparison, the failure is considered to be a bond failure.

A column headed Type of Failure is added in TABLE VI to designate the particular type of failure which will now be described further. The primary mode of failure was that shown in FIGURES 26 and 27. An inverted cone of concrete, hereafter referred to as a "tension cone", separated from the concrete block at ultimate load and remained fixed to the reinforcing bar. The portion of the bar below the cone pulled out of the concrete leaving a smooth hole. The tension cone varied in size, depending on the embedment length of the bar. The largest diameter of the base of the cone varied from about 1 to 8 times the embedment length. This ratio increased with a decrease in the embedment length. The depth of the cone varied from about 0.13 to 1.00 times the embedment length. The average was around 0.5 to 0.6. This ratio also increased as the embedment length decreased.

For the longer embedded bars, a smaller tension cone developed first followed by a larger cone at the failure, as shown in FIGURE 27. FIGURES 28 and 29 show small and large tension cones removed from the block. FIGURE 28 shows a smaller tension cone which has been removed from the bar and placed upside down near the bar. FIGURE 29 shows half of a large cone removed. The bottom edge of the cone has been outlined, and the hole left by the reinforcing bar is outlined with a

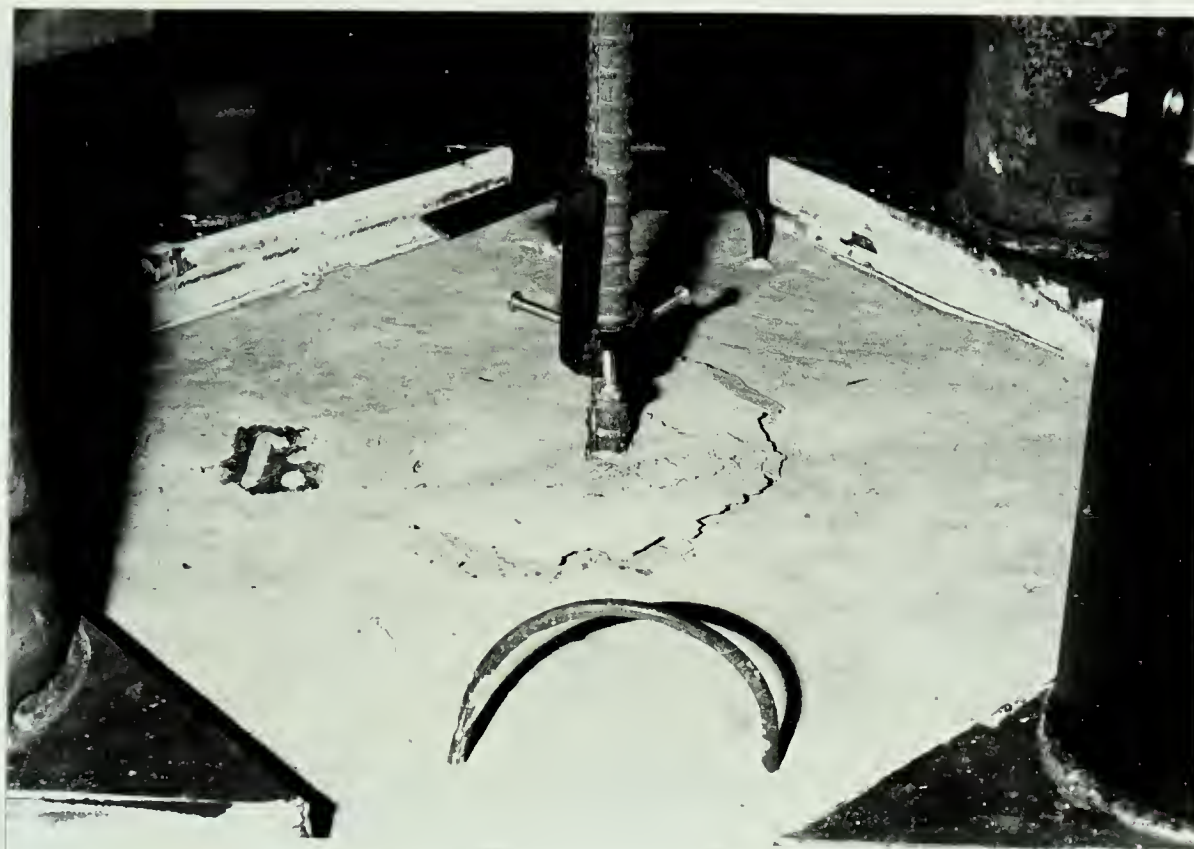


FIGURE 26

FAILURE OF BLOCK PULL-OUT TEST

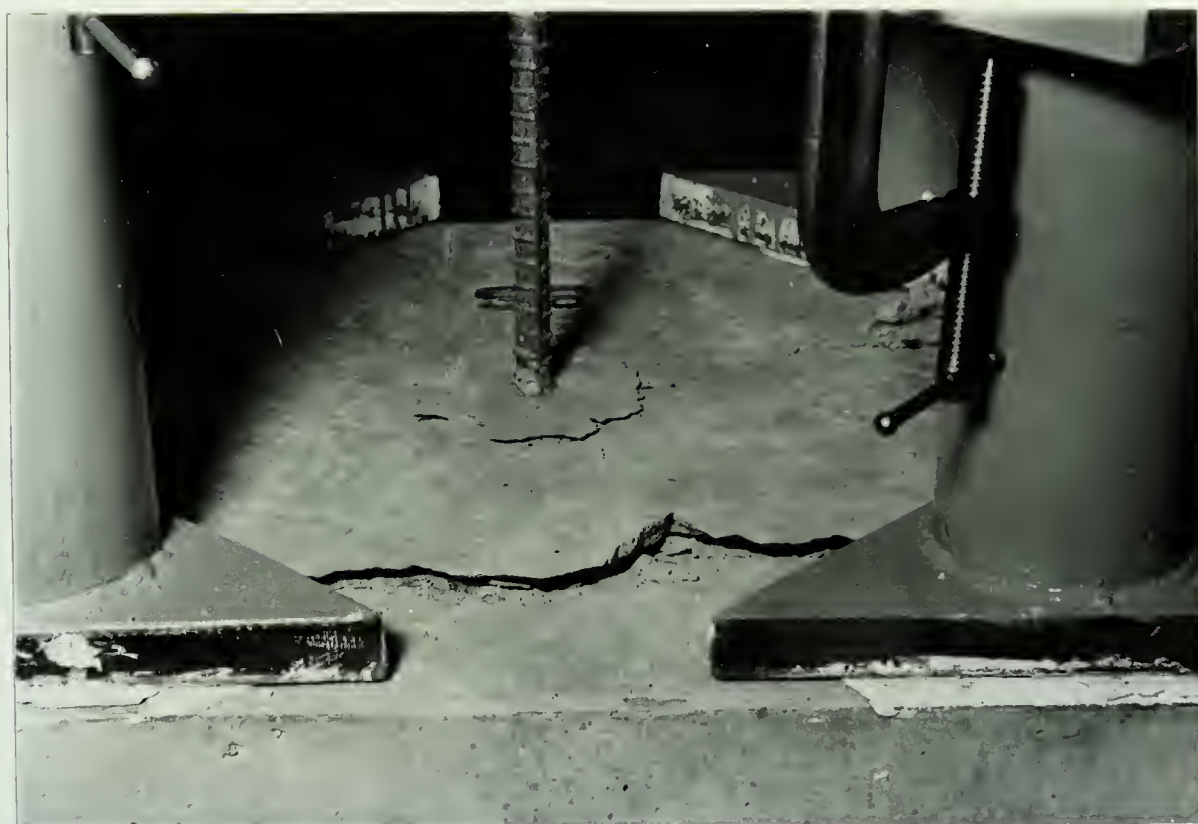


FIGURE 27

FAILURE OF BLOCK PULL-OUT TEST

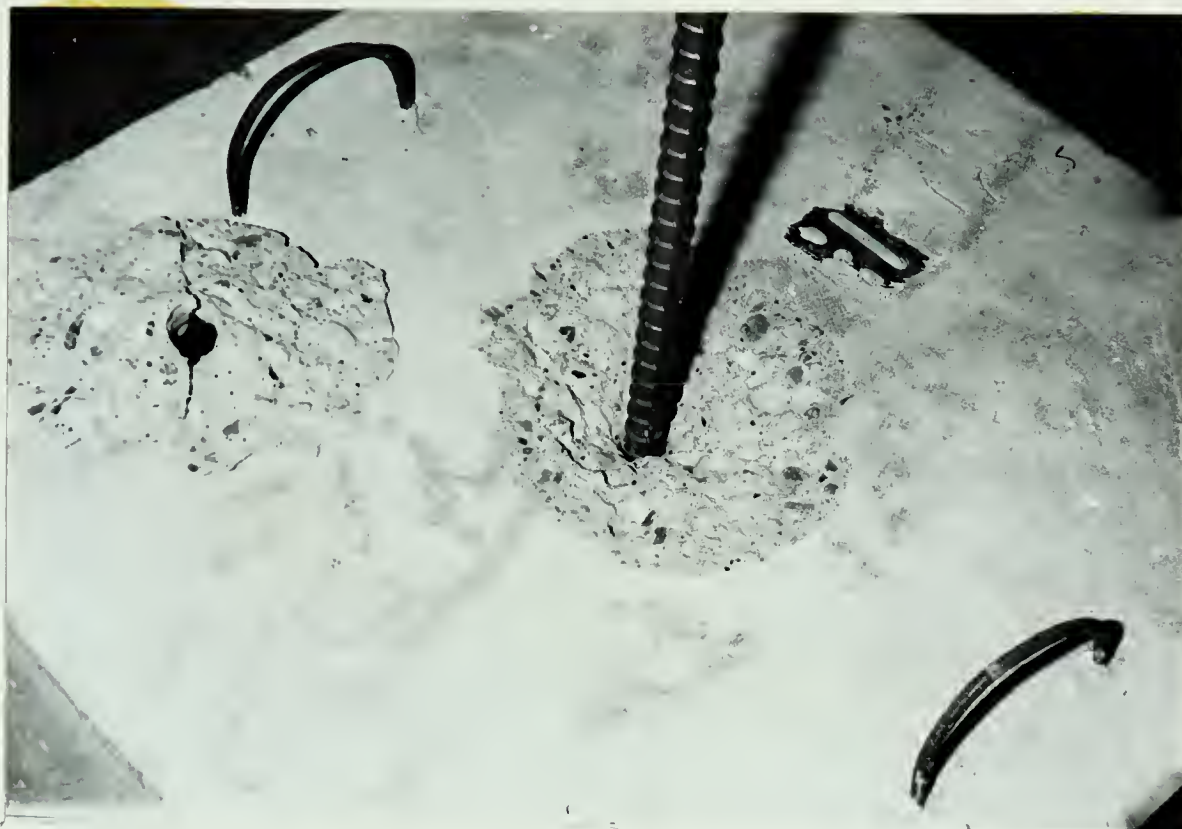


FIGURE 28

TENSION CONE IN BLOCK PULL-OUT TEST



FIGURE 29

TENSION CONE IN BLOCK PULL-OUT TEST

broken line.

This type of tension cone failure can be explained in the following manner: the high local bond stress near the loaded end of the bar caused excessive straining of the bar which induced transverse cracks in the concrete. Upon further straining, these cracks propagated further causing a cone to develop. Most of the load was then transferred to the portion of the bar below the cone. This portion developed high bond stress and behaved similar to an ordinary pull-out test until ultimate failure occurred.

FIGURE 30 is a plot of Reduced Ultimate Bond Resistance versus L/d ratio. The ultimate bond resistance for a particular L/d ratio was taken as the average of the specimens with that L/d ratio for each particular bar size. All specimens were considered to fail in bond. Those which failed by splitting of the block were included because it was not definitely known if the actual failure was due to bond or splitting of the concrete due to flexure. As observed in FIGURE 30, the curves are quite different than normal ultimate bond resistance curves.

The curves can be divided into basically two portions; that to the left of the peak, and that to the right. The portion to the right of the peak tends to exhibit the normal characteristics of ultimate bond resistance versus L/d curve. This portion, therefore, is primarily characterized by a bond failure. Although there was a tension cone formed, there was still enough bar embedded to develop a relatively large bond resistance. The portion to the left of the peak exhibits

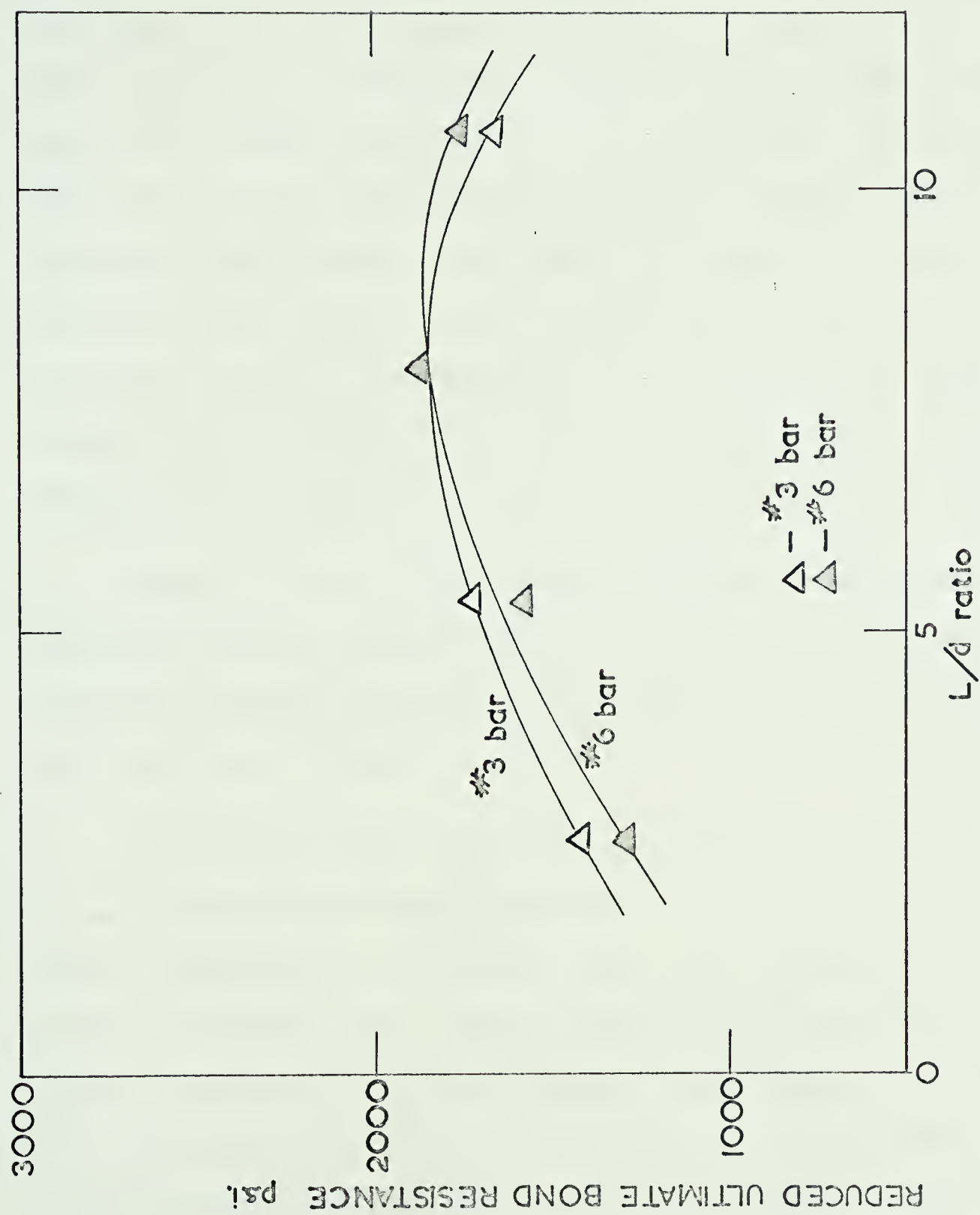


FIGURE 30 REDUCED ULTIMATE BOND RESISTANCE vs.
L/d FOR BLOCK PULL-OUT TESTS

opposite behavior to a normal curve. This can be attributed mainly to the formation of the tension cone. For the very low L/d ratios, the depth of cone was very near or equal to the total embedment length, which indicates the failure was influenced more by the tensile cracking than by bond failure. The portion of the curve to the left of the peak shows a higher ultimate bond resistance for smaller diameter bars having the same L/d ratio. This behavior is similar to a normal bond failure in that a higher stress is concentrated near the loaded end of the bar, giving a lower average bond resistance for the longer, larger bars. The portion to the right of the peaks begins to exhibit characteristics similar to the Spiral Reinforced Cylinder.

FIGURE 31 shows a graph of Reduced Ultimate Bond Resistance versus the absolute Embedment Length. As was the case with the Spiral Reinforced Cylinder Test results, this comparison separates the curves more than those of FIGURE 30, where the L/d parameter was used.

Bond Stress versus Loaded End Slip curves are shown in FIGURES 32 and 33 for #6 and #3 bars respectively. These curves are quite erratic, especially for the #3 bar. This can be attributed to the method of measuring slip. The dial gauge for measurements was fixed to the concrete near the reinforcing bar. Upon loading of the bar, this fixed point would rise with the tension cone in most cases, thereby giving erroneous readings. This fault was not recognized until after the testing program was completed.

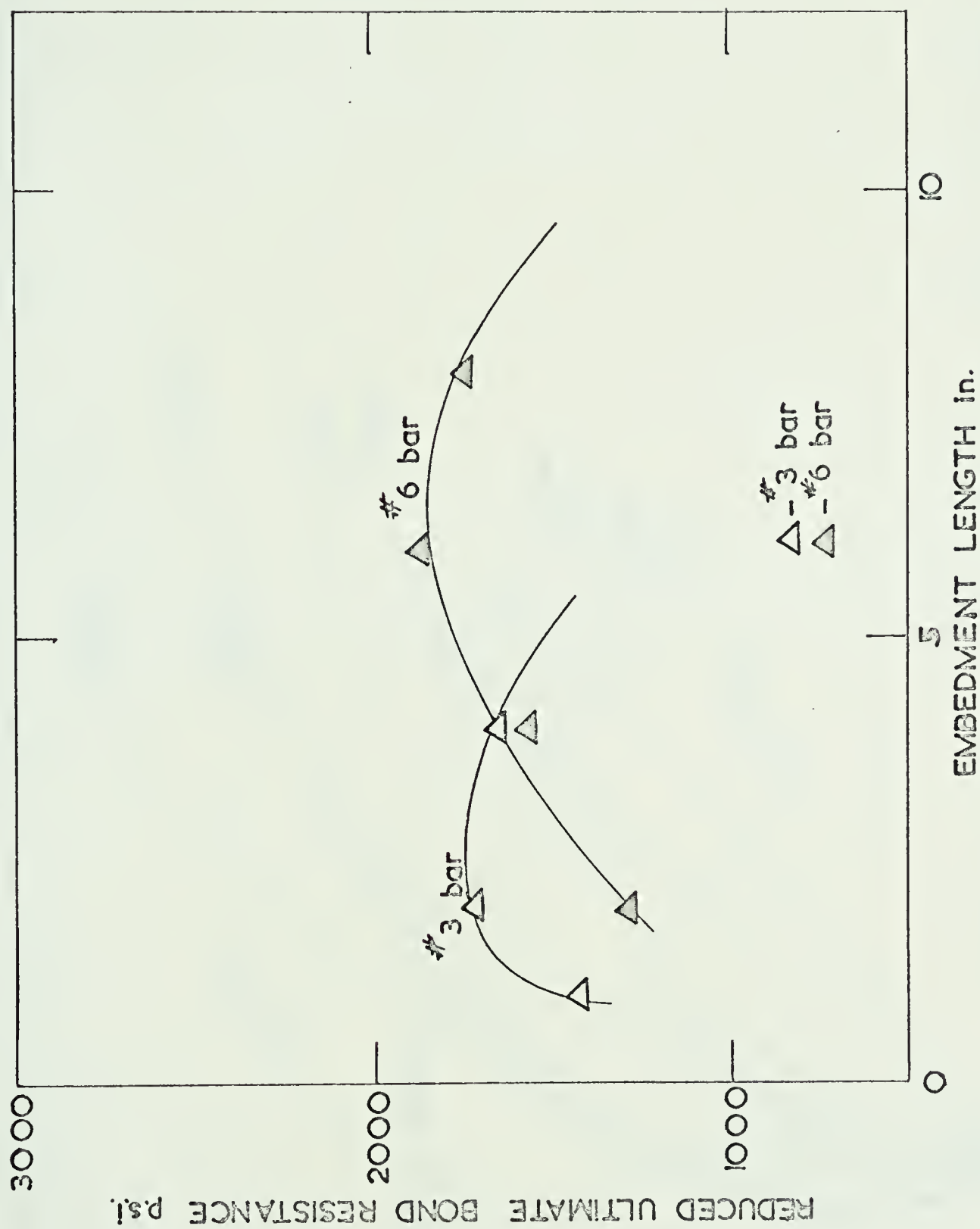


FIGURE 31 REDUCED ULTIMATE BOND RESISTANCE VS. EMBEDMENT LENGTH FOR BLOCK PULL-OUT TESTS

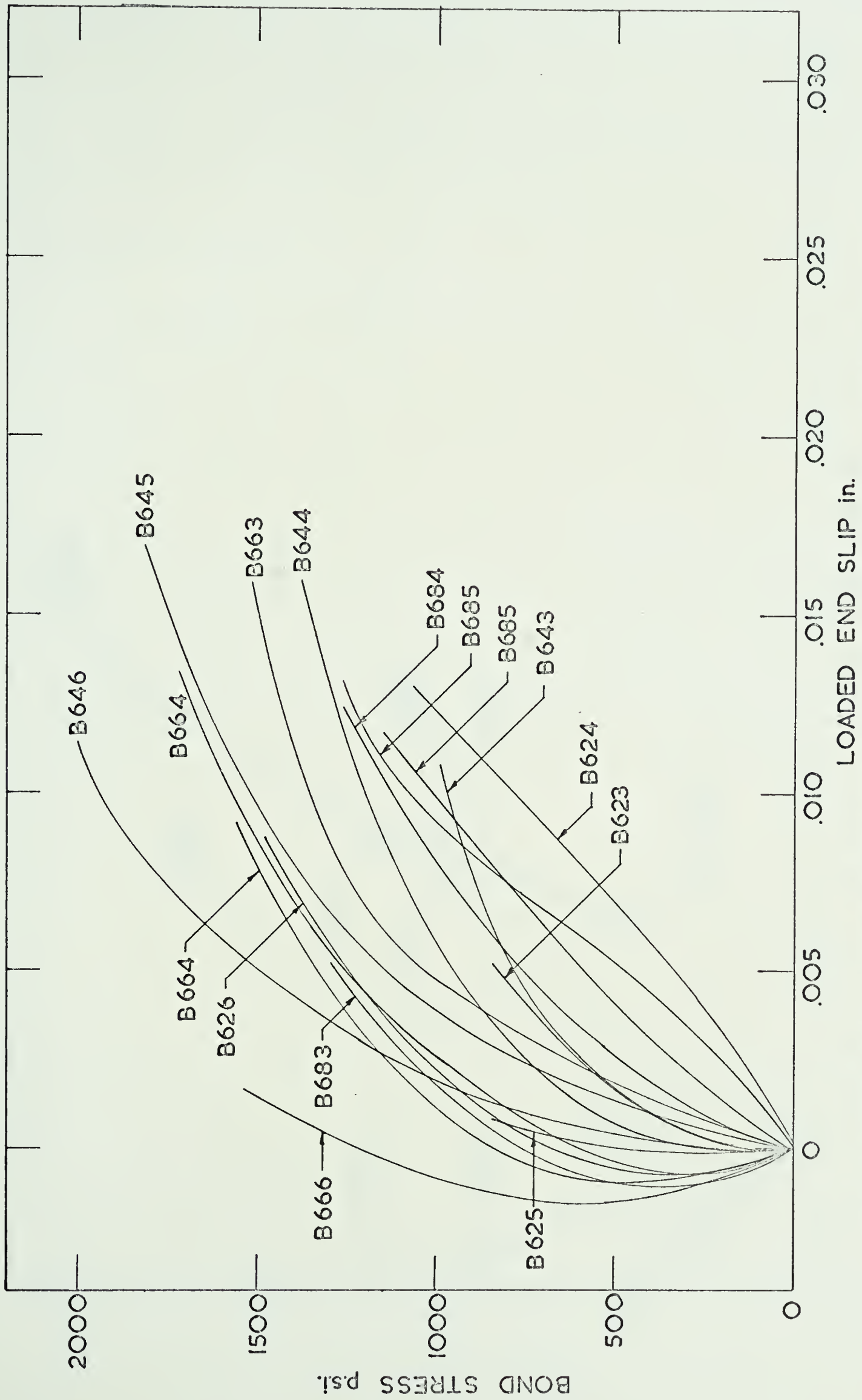


FIGURE 32 BOND STRESS VS. LOADED END SLIP
FOR #6 BAR IN BLOCK PULL-OUT TESTS

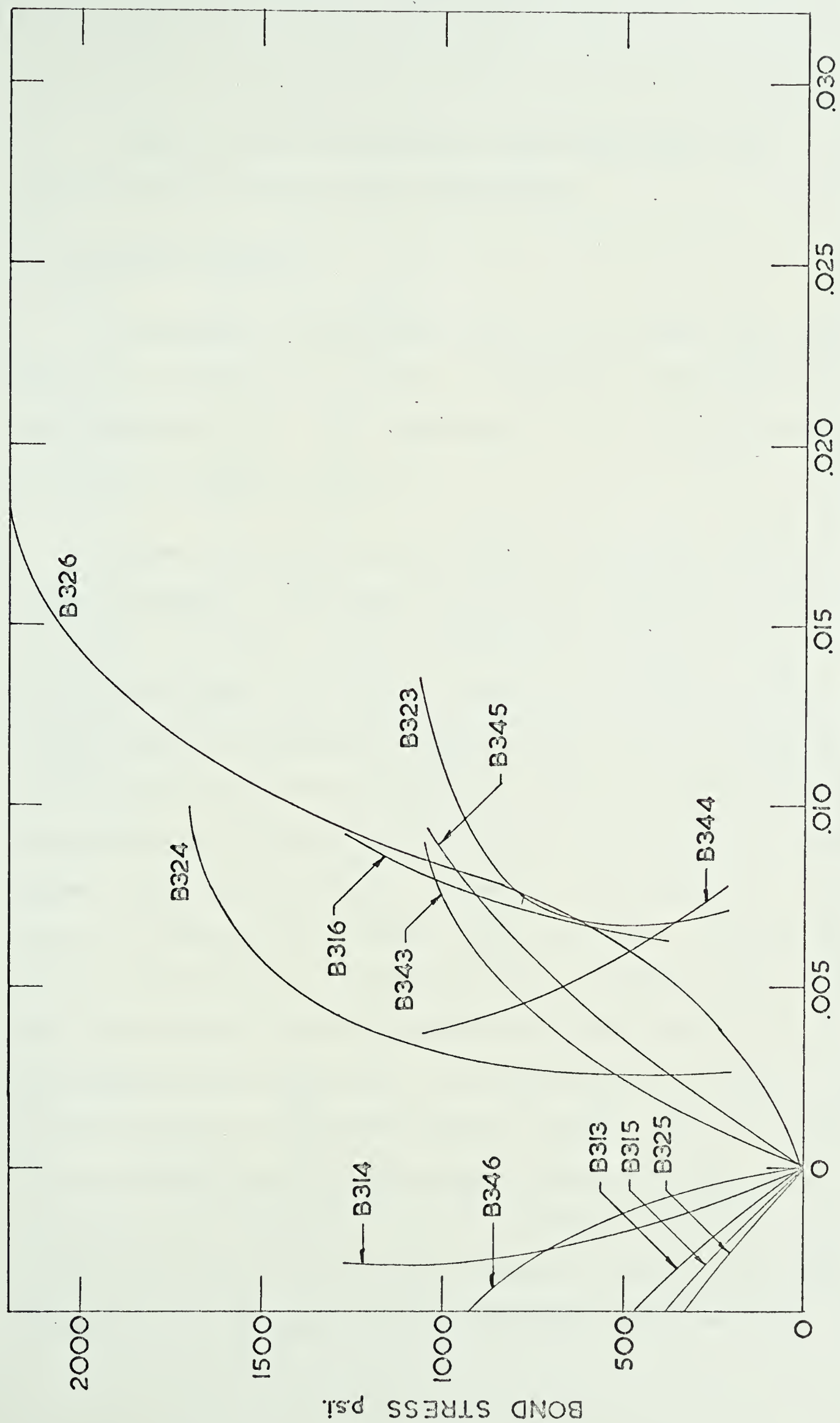


FIGURE 33 BOND STRESS vs. LOADED END SLIP
FOR #3 BAR IN BLOCK PULL-OUT TESTS

Because of the unreliability of slip measurements, no conclusions are drawn from those measurements.

5. Comparison of Tests

A comparison is made between the A.S.T.M., Spiral Reinforced Cylinder, and Block Pull-out Tests. Comparison is made with the L/d and L parameters only. Slip measurements are not considered because of reasons previously mentioned.

Curves for Reduced Ultimate Bond Resistance versus L/d are shown in FIGURE 34. The average value for all the A.S.T.M. Tests falls very close to the curve for the #6 bar embedded 6 inches in the Spiral Reinforced Cylinder Pull-out Test, indicating that the Spirals had little effect in increasing the bond resistance for this particular case. The curves for the Block Pull-out Tests are greatly separated from the Spiral Reinforced Cylinder Tests at low L/d ratios, but come closer together as the L/d ratio increases. The difference at low L/d ratios is because of the different types of failures. At higher L/d ratios, both failures are bond type failures, following similar curves. The curves for the Block Pull-out Tests are lower because of the development of the tension cone. At ultimate load, the resistance is supplied mainly by the embedded portion of the bar below the cone and by some tension in the concrete on the surface of the cone. The remainder of the embedded portion has to develop a stress about 2 or 3 times the average for the entire embedded bar, which is very high. Comparison with the Spiral Reinforced Cylinder Tests shows this is the

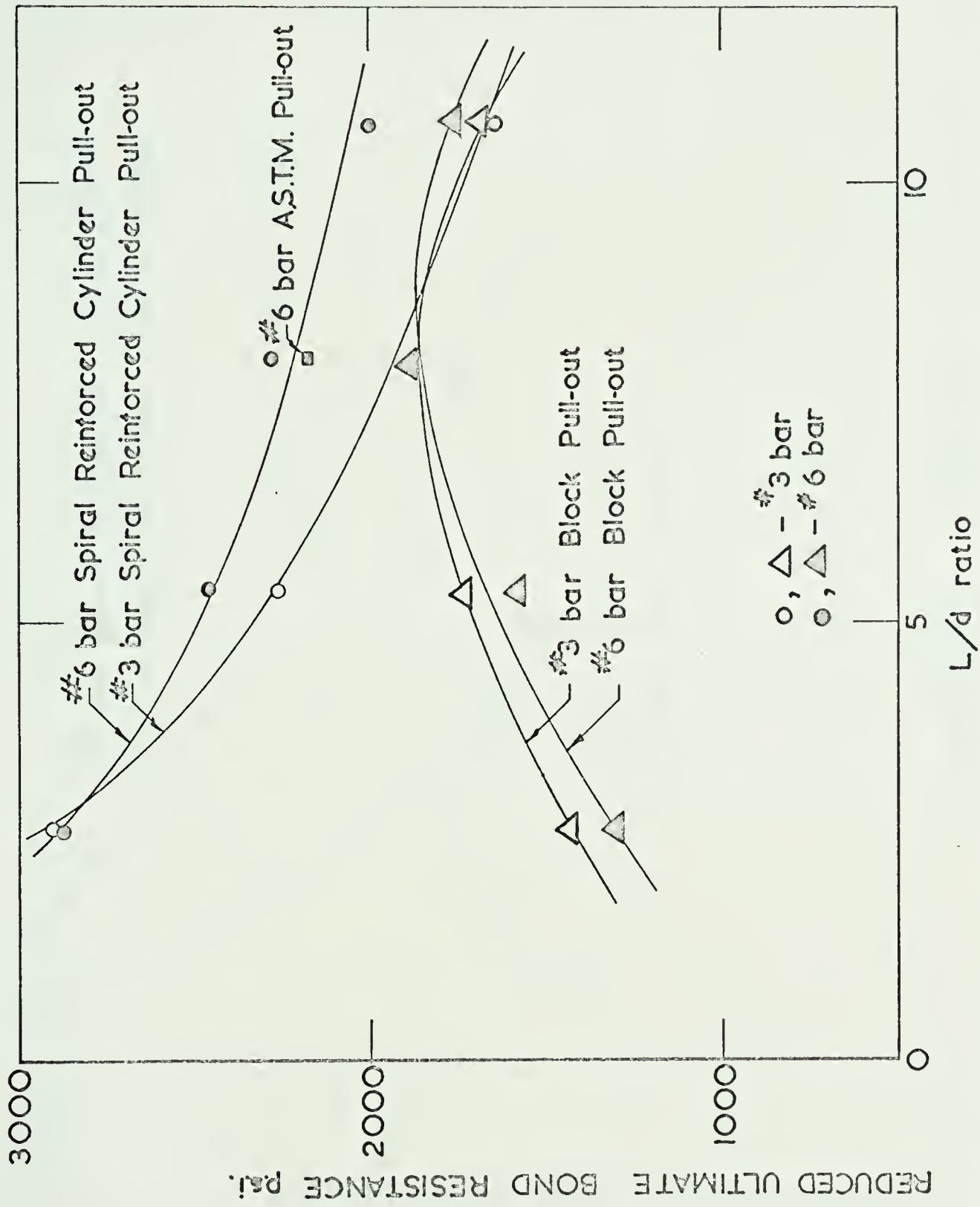


FIGURE 34 REDUCED ULTIMATE BOND RESISTANCE vs.
L/d FOR ALL PULL-OUT TESTS

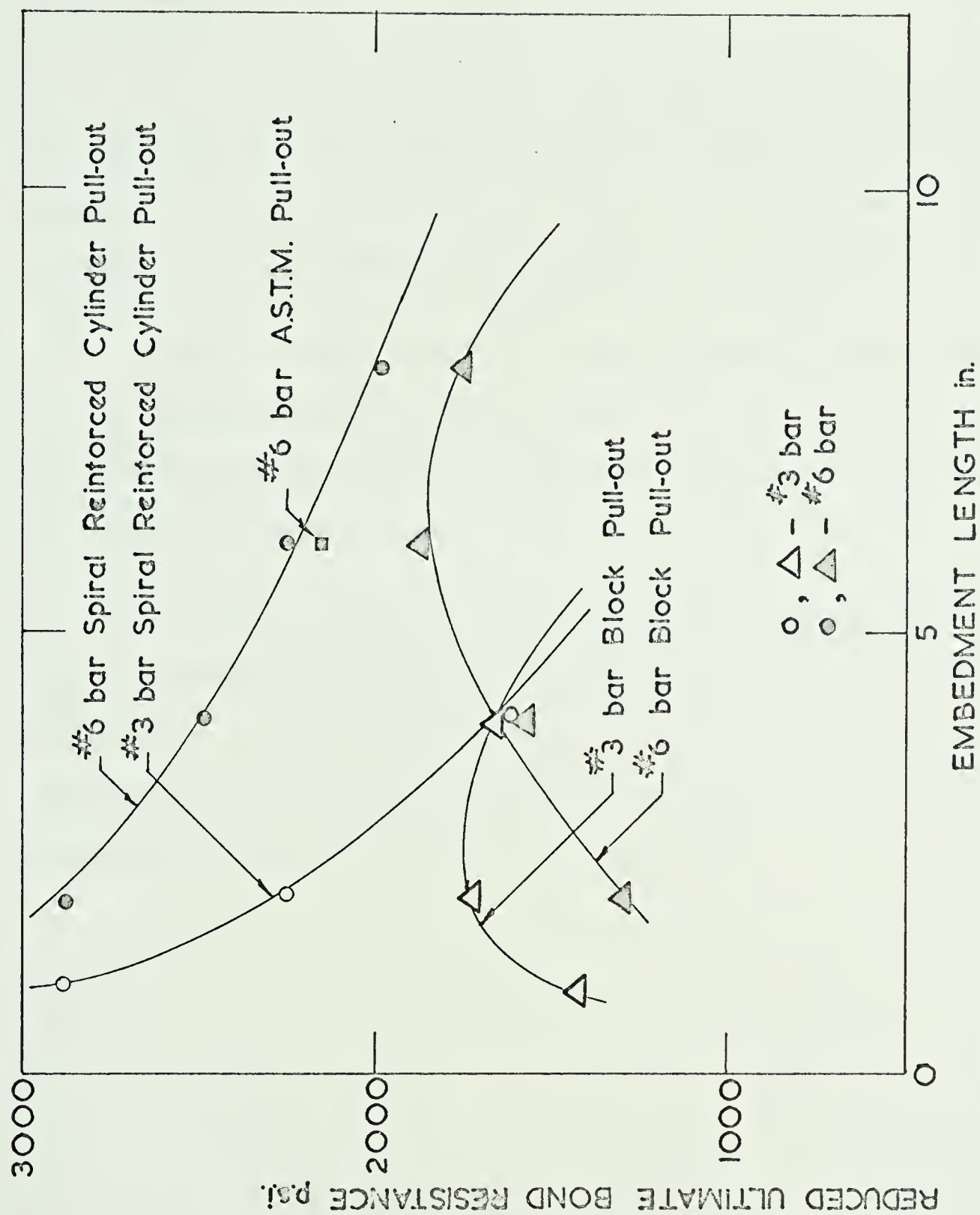


FIGURE 35 REDUCED ULTIMATE BOND RESISTANCE vs. EMBEDMENT LENGTH FOR ALL PULL-OUT TESTS

case. It seems that the curves for the Block Pull-out and Spiral Reinforced Cylinder Tests might coincide for L/d ratios larger than those tested.

The #3 bars in the Block Pull-out Tests exhibit larger ultimate bond resistance than the Spiral Reinforced Cylinder Pull-out Tests for larger L/d ratios. This may be a result of the small number of tests conducted and the average may not have given a true representation.

FIGURE 35 shows curves for Reduced Ultimate Bond Resistance versus Embedment Length for all the tests. The comparisons are similar to those using the L/d parameter, except that the curves are separated more than if the L/d parameter is used.

Overall, the results of the conventional pull-out tests compare quite favorably with previous investigations, except for the higher resistances in larger diameter bars for the same L/d ratios. The Block Pull-out Tests exhibited different characteristics, as would be expected, giving two different types of failures.

CHAPTER VIII

SUMMARY AND CONCLUSIONS

The object of this thesis was to study further the bond between concrete and reinforcement. Three types of tests were conducted, namely; a standard A.S.T.M. Pull-out Test, a Spiral Reinforced Cylinder Pull-out Test in which a concrete cylinder reinforced with spiral wire around an embedded bar was pulled out bearing against the concrete, and a large Block Pull-out Test in which a bar was pulled out by bearing against the extreme corners of a concrete block in which the bar was embedded. The Block Pull-out Test was intended to eliminate any direct effects of bearing on the concrete near the reinforcing bar during testing.

The variables studied were: concrete compressive strength, bar size, and embedment length.

The results of the A.S.T.M. Pull-out Tests agreed with results of previous investigators in that the ultimate bond resistance varied as $\sqrt{f_c'}$. Tests of the Spiral Reinforced Cylinder Pull-out specimens also exhibited this behavior for most L/d ratios, but enough tests were not carried out to conclude this was definitely the case for all L/d ratios. The Block Pull-out Test results indicated the same characteristics, but it should be noted that the failure was not

completely a bond failure; in some cases it was more of a tensile failure of the concrete.

For the Spiral Reinforced Cylinder Pull-out Tests, the ultimate bond resistance decreased with an increase in the L/d ratio, but for the same L/d ratio, the #6 bar exhibited greater bond resistance than the #3 bar. This was probably due to the development of a very high bond resistance near the unloaded end of the bar in the larger, longer embedded bar.

Behavior of the Block Pull-out Test was quite different. For low L/d ratios, the ultimate bond resistance was low because the failure was primarily a tensile failure of the concrete. For higher L/d ratios, the bond resistance increased to a peak, then decreased as the failure approached a typical bond failure.

The main conclusion of this thesis is that the Block Pull-out Test does not seem to show much promise as a pull-out test. Because of its size and different modes of failure, it is not as good as a conventional pull-out test. It shows no promise of comparison with beam tests.

CHAPTER IX

RECOMMENDATIONS

After studying the results and conclusions there are still some problems which have to be solved and some areas which require further study.

1. Problems Encountered

The main problem encountered was in the method of slip measurement at the loaded end of the bar. For the A.S.T.M. and Spiral Reinforced Cylinder Pull-out Tests, loosening of the yoke clamped to the bar near the loaded end forced termination of measurements after the steel had yielded. If a better method of fixing the yoke to the bar could be devised, slip measurements could be taken right up to the failure load. This would not give true slip values because of excessive straining in the steel, but could give another basis for comparing bond behavior. A possible solution to the problem would be to lightly tack weld the yoke to the reinforcing bar before testing. If properly done, this should not damage the bar or surrounding concrete and the welds could easily be broken after testing to permit repeated use of the yoke.

If further tests on the Block Pull-out specimen are conducted, the method of measuring slip should be revised as the results from

present testing were very poor. First of all, a type of double yoke similar to that used for the other tests should be used to compensate for any slight bending of the bar during loading. This could be accomplished by placing another "foot" on the opposite side of the existing "foot". Tack welding the collar to the bar would help to solve the problem of loosening of the yoke after yielding.

The method of fixing the dial gauges to the Block Pull-out should also be revised. In the tests conducted, the dial gauge base was in the concrete adjacent to the reinforcing bar and lifting of the tension cone caused false readings of slip. A solution might be to fix the dial gauges to the sides of the concrete block, or to the testing frame. This would prevent movement of the dial gauges relative to the initial concrete surface, and give an absolute value of slip.

2. Areas of Further Study

A study of the bond stress distribution along the embedded reinforcing bar would be a most interesting study. It would prove or disprove the author's hypothesis of the development of high local bond stress near the unloaded end of the bar at ultimate conditions. This study could best be applied to the Spiral Reinforced Cylinder and Block Pull-out Tests. This type of study could be conducted using the procedure by Mains (1951) or perhaps using very small electrical resistance strain gauges placed on the surface of the bar. The latter method may be impractical because it would require difficult concrete placement which may result in poor bond characteristics. The strain

gauges would have to be small enough so that the bond mechanism near each gauge is not interrupted.

Another area requiring further study is the behavior of tests with larger L/d ratios. This would be helpful to check if there is a further correlation between the Spiral Reinforced Cylinder and Block Pull-out Tests. This can be accomplished by using higher strength reinforcing bars so more load can be applied to the larger and longer bars.

It would be interesting to conduct tests similar to the Spiral Reinforced Cylinder Test, but excluding any spiral reinforcement. As there was little difference in ultimate bond resistance between the A.S.T.M. and Spiral Reinforced Cylinder Tests as conducted, the same may be true for tests over the full range of L/d ratios. If this is true, the exclusion of reinforcement would save time in the fabrication of pull-out specimens.

It may be also worthwhile to conduct pull-out tests similar to those done by other researchers who used slip as a failure criterion. Comparison of both values for failure might prove useful in knowing the reserve capacity after an "unservicable" failure has occurred.

Of these recommendations, the author considers the stress distribution study the most important and the one that should be conducted next in the series.

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